TO WHICH EXTENT CAN ATTENTION AND/OR ATTENTION MODULATION EXPLAIN DEFICITS IN DYSLEXIA?

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ASTON UNIVERSITY

October 2014

Aston University

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Thesis Summary

This thesis investigates the visual deficits associated with developmental dyslexia, particularly that of visual attention. Visual attention has previously been investigated in a wide array of behavioural and psychophysical (amongst others) studies but not many have produced consistent findings. Attention processes are believed to play an integral part in depicting the overall "extent" of reading deficits in dyslexia, so it was of paramount importance to aim at such attention mechanisms in this research.

The experiments in this thesis focused on signal enhancement and noise (distractor) exclusion. Given the flexibility of the visual search paradigms employed in this research, factors such as visual crowding and attention distribution was also investigated. The experiments systematically manipulated noise (by increasing distractor count, i.e. set-size), crowding (varying the spacing between distractors), attention allocation (use of peripheral cues to direct attention), and attention distribution (influence of one visual field over the other), all of which were tied to a critical factor, the "location/spatial/decisional uncertainty".

Adults with dyslexia were: (i) able to modulate attention appropriately using peripheral pre-cues, (ii) severely affected by crowding, and (iii) unable to counteract increased set-sizes when post or un-cued, the latter signifying poor distractor (noise) suppression. By controlling for location uncertainty, the findings confirmed that adults with dyslexia were yet again affected by crowding and set-size, in addition to an asymmetric attention distribution. Confounding effects of ADHD symptoms did not explain a significant independent variance in performance, suggesting that the difficulty shown by adult dyslexics were not accounted for by co-morbid ADHD. Furthermore, the effects of crowding, set-size and asymmetric attention correlated significantly with literacy, but not ADHD measures.

It is believed that a more diffuse and an asymmetric attention system (in dyslexia) to be the limiting factor concerning noise exclusion and attention distribution. The findings from this thesis add to the current understanding of the potential role of deficits in visual attention in dyslexia and in the literacy difficulties experienced by this population.

Key words: Dyslexia, Attention, Noise Exclusion, Visual Crowding, Asymmetric Attention

Dedication

بسم الله الرحمن الرحيم

"In the name of Allah, Most Gracious, Most Merciful."

First of all, I'd like to thank Almighty Allah (*Subhanahu Wa' Ta'ala*, SWT) for providing me with the sound intellect, along with the mental and physical courage to successfully hurdle through the entire duration of my doctorate here at Aston University, Birmingham - UK.

This thesis is dedicated to two central sources for their remarkable support in many ways.

Firstly, I dedicate this thesis to my dearly loving parents for all their constant sacrifices, the faith they had in me and the prayers they made on my behalf in seeing me succeed to what has been a 10 year long academic journey. It was both my mother (Mrs. Jesima Jainulabdeen) and father (Dr. Seyed Cassim – Homeopathic Medicine) who drove me cautiously throughout the journey of academia illustrating the delight of intellectual pursuit. It is from these two humble guardians that I learnt the best kind of knowledge ones got to cherish are those which have been cultured for its own value. Now, I realize the value of this abundant knowledge, thanks to this prestigious PhD degree and *In'sha'Allah* (By The Will of Allah) I look forward for much more that bestows upon me in the coming future.

Secondly, I'd like to dedicate this thesis to my beloved wife and soulmate (Dr. Sajeeha Saleeth – MBBS) who has been a constant source of motivation and support right from the word go. In short, she resembled the shadow of my own soul despite being oceans apart, who constantly strove to keep my motivation levels up even when the going was extremely tough. Same applies to my loving in-laws for being there with me and my family during this most important juncture of my academic life.

Not to mention, this thesis is all but a small token of appreciation and sincere gratitude for all the sacrifices and struggles which these special people in my life have gone through just to see me where I am today. May Almighty Allah (SWT) bless them always - Aameen.

Acknowledgements

This thesis was the making of precisely fifty seven hard working months of research since embarking with the Cognitive and Affective Neurosciences Research Group at Aston University. During my time at Aston, the lovely people I've worked with, and those who contributed immensely to this research in many ways deserves special mention. It is therefore a pleasure to convey my humble gratitude to the following.

Firstly, I would like to thank my supervisor (Dr. Liz Moores) for her excellent supervision from day one when she set the tone in getting the ball rolling. Her clever advices, insightful criticisms, patient encouragement along with guidance and one-to-one support provided me extraordinary ways of overcoming pitfalls in innumerable ways. Her intuition as an expert Psychologist and with the kind of passion she had towards her work has undoubtedly motivated and enriched my development as a research student and a future neuroscientist-to-be. I am indebted to her more than she knows for being there for me at every knock on the door to ensure that I succeed.

Secondly, I would like to thank my associate supervisor (Professor Joel B. Talcott) for his steadfast advice and critical insights making him the ideal backbone of this research. The originality he possessed and the diverse background information he instilled me over time has certainly nourished my intellectual maturity, and this undoubtedly is something which I shall benefit from in the long term.

Thirdly, I would like to thank Dr. Olivia Longe for her steadfast neuroimaging support during lab training (along with Dr. Craig McAllister), examination, in addition to the one-to-one tutorial sessions. Much to my disappointment, it was heart breaking not having the chance to complete the fMRI study (study 4) in full due to circumstances beyond my control.

I would like to extend my sincere gratitude to all the participants who took part in the research studies. A huge vote of thanks also goes out to my office colleagues (SW506) for offering me a helping hand during the pilot stages. Furthermore, the regular journal clubs run by both PhD and Post-Doc psychology researchers created a positive impact on my critiquing skills, in addition to gaining a deeper understanding in my field of research.

Last but not least, I would like to say a big **THANK YOU** to the whole of Aston University for their wonderful facilities and very helpful members of staff for all their warm hospitality.

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Research Articles generated from this Thesis

Study 2 (Chapter 3):

Cassim, R., Talcott, J.B. and Moores, E. (2014). Adults with dyslexia demonstrate large effects of crowding and detrimental effects of distractors in a visual tilt discrimination task. PLoS One. 9(9): e106191. DOI: 10.1371/journal.pone.0106191.

Study 3 (Chapter 4):

Moores, E., Cassim, R. and Talcott, J.B (2011). Adults with dyslexia exhibit large effects of crowding, increased dependence on cues, and detrimental effects of distractors in visual search tasks. Neuropsychologia, 49, 3881-3890. DOI: 10.1016/j.neuropsychologia.2011.10.005.

Chapter 1:

General Introduction

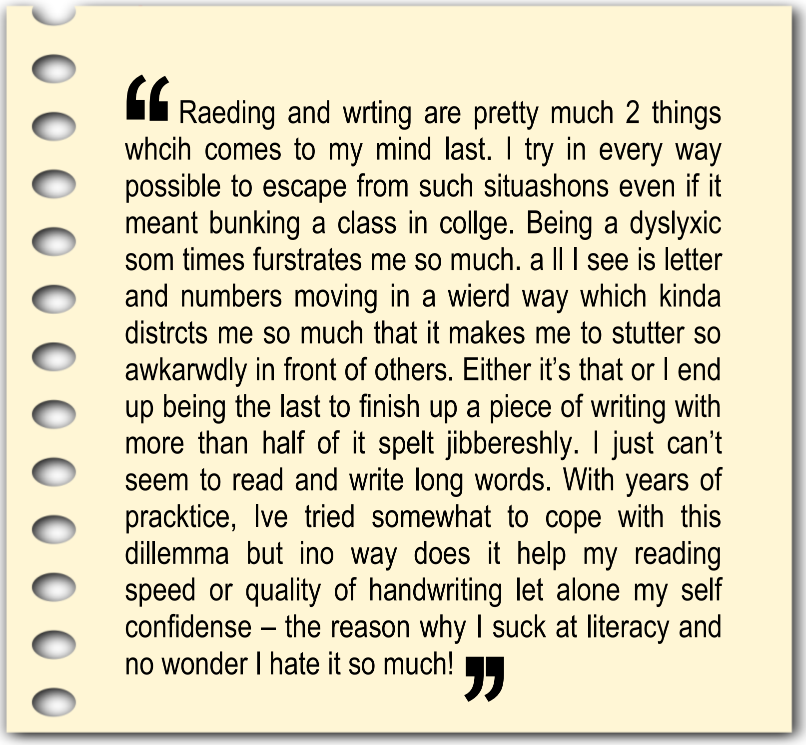
1.1 Chapter Overview

This chapter presents a general introduction into reading and it's manifestation in developmental dyslexia. The principle theories of developmental dyslexia will be discussed backed up by supporting evidence. Also included is the discussion of areas within these theories that yield disagreement in terms of providing a causal explanation of dyslexia. Later in the extract, more emphasis will be shed towards the visual component where the importance of attention in mediating efficient reading is highlighted. The major theories of attention will also be discussed at length, and how such deficits in visual attention alone could play a part in dyslexia.

1.2 Developmental Dyslexia – Setting the scene

Reading is an interactive process by which an individual decodes the printed symbols in order to construct their meanings in a manner where they are then able to communicate efficiently. Although the ability to read is not considered to be a skill that evolves over time compared to language acquisition, it's still an important aspect for a child's development. It was not until 1700 BC that the intervention of reading took place and since then the ability to read efficiently has taken a strong hold towards an understanding of the explicit hardware associated, in particular the plasticity and capacity of the human brain structures. Importantly though, reading employs a multitude of complex internal functions ranging from scanning of the eyes, matching letter or combination of letters (graphemes) accordingly to represent corresponding sounds (phonemes) and/or form words (orthography), through to exploitation of a spacious attention span. Regardless of the multiple brain regions which are employed to perform such a complex task, what's even more surprising is the ease and fluency that a mediocre reader is capable of attaining in order to become a proficient reader. Therefore, this transition period, or the point at which reading becomes automatised becomes quite crucial in terms of attaining the required literacy level with respect to age.

However, certain individuals find it quite hard to fully attain literacy that is both effortless and fluent, which is quite expected given the cognitive requirements of such a demanding task. For example, **figure 1** demonstrates the sort of feedback obtained from an adult participant [X] when asked about how she felt regarding a developmental disorder which she had been suffering from her early childhood. This is what she had to come up with in writing (represented here in an electronic form).



“Raeding and wrting are pretty much 2 things whcih comes to my mind last. I try in every way possible to escape from such situashons even if it meant bunking a class in collge. Being a dyslyxic som times furstrates me so much. a ll I see is letter and numbers moving in a wierd way which kinda distrcts me so much that it makes me to stutter so awkarwdly in front of others. Either it’s that or I end up being the last to finish up a piece of writing with more than half of it spelt jibbereshly. I just can’t seem to read and write long words. With years of pracktice, Ive tried somewhat to cope with this dillemma but ino way does it help my reading speed or quality of handwriting let alone my self confidense – the reason why I suck at literacy and no wonder I hate it so much! ”

Figure 1: How does it feel like to be in the shoes of an individual having poor literacy skills? Note the serious grammatical errors. Apart from the emotional stance, the problem that this individual encounters is far from what it is replicated in observable terms.

If this was to be written down by a competent user free from any developmental disorder, matched for age, gender and education, then it would have looked something like:

> "*Reading and writing are pretty much two things which comes to my mind last. I try in every way possible to escape from such situations even if it meant bunking a class in college. Being a dyslexic sometimes frustrates me so much. All I see is letters and numbers moving in a weird way which kind of distracts me to stutter so awkwardly in front of others. Either it’s that or I end up being the last to finish up with a piece of writing with more than half of it spelt jibberishly. I just can’t seem to read and write long words. With years of practice, I’ve tried somewhat to cope with this dilemma but in no way does it help my reading speed or quality of handwriting let alone my self confidence – the reason why I suck at literacy and no wonder I hate it* so much! "

Participant [X], like her normally reading counterpart, demonstrated good reasoning skills and education having pursued an undergraduate degree in the recent past. But what is more interesting is the inability to acquire adequate literacy skills such as single word reading and spelling (**figure 1**), which occurred independently of her level of intelligence and general cognitive functioning (e.g. visual perception, thinking capacity, level of reasoning, recall and remembering, etc). Additionally, it was evident that she also had problems related to recognition of familiar words, left and right discrimination, among a whole battery of other deficits (will be described as we go along), a cognitive profile referred to as developmental dyslexia.

Developmental dyslexia (henceforth, dyslexia) is recognised as the most common of the developmental disorders known to-date signifying at least two thirds of all specific learning difficulties (Shaywitz & Shaywitz, 2003). It is estimated that around 6 - 17% of the school age population and around 5 - 7% of the entire population demonstrate poor performance in reading compared with age and reading-matched peers, whilst otherwise demonstrating a generally high IQ (Fletcher, Lyon, Fuchs, & Barnes, 2007). The prevalence rate for dyslexia are typically on the higher side for males compared to females on a ratio of 3:1 (Pennington, 2009), most likely due to the high occurrence of behavioural problems in males (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). This is thought to be a far greater estimate to prevalence rates of various other developmental disorders such as autism. Furthermore, there is a higher pattern of co-morbidity displayed between dyslexia and other developmental disorders such as dyspraxia, and particularly with that of attention-deficit hyperactivity disorder (ADHD). Therefore, it is of prime importance to avoid such symptoms from linking dyslexia to other developmental disorders (e.g. poor balance, with the end result being either ADHD or development coordination disorder: Rochelle & Talcott, 2006). Nevertheless, given that dyslexia is overrepresented in clinical populations with a wide array of mental health problems, the key however is to provide psychiatric interventions which focuses on either eradication of the symptom or aid progression through normal development. However, the cut-off point between dyslexic and non-dyslexic symptoms is entirely based on subjective responses, which at the time had further led to several controversies in the realm of dyslexia as a developmental disorder. To make matters even more confusing, scholars who attempted to compile findings in dyslexia have left the reader with a seemingly continuous list of hypotheses and possibilities. As we begin our journey into this literature, it is important to indentify the nature of this disorder to better understand the complexity and the underlying deficits that lead to poor literacy and other cognitive deficits observed in both children and adults with dyslexia (C&AwDys).

1.3 Defining dyslexia

Dyslexia has been one of the most intensely studied subjects in developmental psychology. One question which startled many scholars at the earliest stages of research was the precise definition of dyslexia. The primary concern in trying to study a complex development disorder such as this is that C&AwDys often displayed varying levels of shortcomings primarily in the areas governing reading, spelling and writing. Studies which assessed these abilities in individuals with dyslexia have generally yielded literature which is patchy in certain areas, rendering a level of ambiguity given the involvement of various dependent variables upon which the term rests. The grassroots of the word "dyslexia" comes from the two Greek syllabuses, *dys* (meaning some form of difficulty), and *lexis* (meaning a particular word). According to the psychiatric classification (DSM–IV), dyslexia is referred to as a "reading disorder" classed under the category "learning disorders" (American Psychiatric Association, 1994). In the United Kingdom, the term "specific learning difficulties/disorder" has been much more of a preferred choice by both the educational institutionalists and mainstream psychologists. When describing specific reading disorder, DSM–IV in actual fact entails that the reading skills be significantly below an expected threshold based on an individual’s age, age-appropriate education, IQ and emotional deprivation. These dependent variables were expected to be sufficient to significantly hamper the academic achievement and/or activities that required normal developmental tasks, thus forming an exclusion criterion. However, the major problem with this descriptive statement is such that, it solely highlights a psychometric meaning while excluding the underlying cognitive processes involved.

In an attempt to categorize poor readers, the use of IQ-achievement discrepancy has played a vital part given a wide spectrum of learning disabilities and their characteristic symptoms. The discrepancy criterion entails that a dyslexic individual should have a minimum IQ of 90, along with a reading age of at least two years short of their chronological age group. The fundamental conjecture here is that an individual with an average IQ ought to develop normal reading skills. Based on this discrepancy criterion, poor readers were divided into two groups, namely those exhibiting a discrepancy between IQ and reading achievement (dyslexic), and those who did not show such a discrepancy (slow or poor readers). Studies which focused on the reading difficulties experienced by such a mixed population arrived at several reasons as for the importance of redefining this "discrepancy definition" for appropriate diagnosis of dyslexia. Critics argued that the discrepancy definition towards linking IQ to reading and spelling achievement doesn’t sit well since it was assumed that IQ predominantly establishes the level of intellect, while intellect had no direct links with literacy achievement itself, that too despite IQ being a general predictor of reading achievement (Siegel, 1989). In fact, findings have showed evidence of such plausible assumptions where a poor correlation between IQ and reading skills was experienced by individuals with dyslexia (Stanovich, 1991). Furthermore, the reading dependent cognitive skills were found to be identical regardless of whether the poor readers had low or high IQ (Stanovich & Siegel, 1994), and that there was a low level response during reading remediation independent of IQ (Vellutino, Scanlon, & Lyon, 2000). One drawback of this IQ-achievement discrepancy was the improper identification of within group differences to bring about a specific intervention in the best interests of that group. Instead, the poor readers were classed in a way where special education needs were catered only in favour of those individuals who showed an IQ-achievement discrepancy compared to those who didn’t. This was based on the principle that individuals with lower IQ’s had a limited reading achievement. This meant that, on one hand, such group of individuals weren’t offered immediate help as they were left to wait till they were in a better position to be identified (by the point at which they had already failed reading). On the other hand, the ones who desperately worked themselves slightly or well above average also ended up being excluded since they weren’t expected to reach the fullest potential based on the prediction that they might also fail. Thus, a major limitation as far as the discrepancy definitions were concerned is the lack of constructive diagnostic principles.

It was not long afterwards, when another proposal for sub-dividing poor readers independent of IQ-discrepancy immerged on the basis of the Reading Component Model (Aaron, 1997), where comparisons between reading and listening comprehension was thought to be a better indicator of poor reading (especially with listening comprehension tested on its own), than did IQ (Palmer, McCleod, Hunt, & Davidson, 1985; Stanovich, 1991). This led to the understanding that poor word reading abilities arose from a specific defect in phonological (speech) processing, i.e. impairment in acquisition of print-to-sound decoding skills. However, critics argued the possible conflation of findings between: the cause of developmental dyslexia with that of poor reading; the involvement of a phonological deficit as a cause compared to a symptom of dyslexia; and the problem of dyslexia being a reading deficit compared to diagnosis and remediation of reading problems as a whole (Nicolson, 1996). For instance, reading comprehension is examined by means where an individual is required to read a passage of text prior to answering the questions based on that passage under a given time limit. Although poor readers with comparatively poor IQ levels (unlike their counterparts) are able to read, they still find it difficult with reading comprehension and this could be due to a case of them being unable to possess the relevant skills to understand the reading material, perhaps due to the sluggishness of reading, or it may be that they do not have sufficient background knowledge to understand the passage/questions at hand. This was in line with Nicolson's proposal where he stated that despite the extent of phonological deficits evident in both individuals with dyslexia and those with below par IQ, the primary cause behind such phonological deficits were by no means identical. It has been further suggested that if one was to precisely define dyslexia a need for a broader view was essential, especially one which was not limited to reading alone (Nicolson & Fawcett, 1990).

The ever expanding research into specific developmental disorders therein enabled scholars from diverse backgrounds to contribute some essence into the formulation of a conclusive definition for dyslexia. Previously, the Orton Dyslexia Society (1994) defined dyslexia as:

> "… one of several distinct learning disabilities. It is a specific language-based disorder of constitutional origin characterised by difficulties in single-word decoding, usually reflecting insufficient phonological processing abilities. These difficulties in single word decoding are often unexpected in relation to age and other cognitive and academic abilities: they are not the result of generalised developmental disability or sensory impairment. Dyslexia is manifest by variable difficulty with different forms of language, often including, in addition to problems of reading, a conspicuous problem with acquiring proficiency in writing and spelling. "

Almost a decade later, the following definition of dyslexia was reiterated in a research article by Lyon, Shaywitz, & Shaywitz (2003), a term previously put forward by the Research Committee of the International Dyslexia Association:

> "Dyslexia is a specific learning disability that is neurobiological in origin. It is characterised by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede growth of vocabulary and background knowledge."

Nothing much has really changed in the definition towards dyslexia following its earlier proposal (Orton Dyslexia Society, 1994). These definitions briefly interpret the most vital facets of dyslexia presently understood. The difficulty in the lack of a concise definition of dyslexia to start with has given way to varying research outcomes and theories. Before we move on to this, it is necessary to appreciate how the understanding of dyslexia evolved.

1.4 The History of Dyslexia

Dyslexia was initially documented in the late 1900's which originated from a neurological deficit, as it showed close resemblance between dyslexia like symptoms and visual/congenital "word blindness". Interest into reading difficulty began when Kussmaul (1877) first introduced the notion of "word blindness" when he noticed that most of the adult patients whom he closely studied could not read properly and regularly as they used words in the wrong order. A few years on, Hinshelwood (1896) and then Morgan (1896) reasoned that the word blindness deficit was a result of a defect which Hinshelwood thought was hereditary, that lingered between the acquisition and the storage of visual imprints (letters and words) in the brain. This further prompted Hinshelwood to classify dyslexic individuals into three groups: dyslexia – for individuals with a minor setback in learning to read; alexia – for individuals with reading disability inclusive of mental retardation; and word blindness – for individuals with severe reading disability (of its purest form). Hinshelwood extended his research interests into clinical case studies, during which time a few other researches had begun relating dyslexia to a deficit in cerebral brain structures such as inherited aplasia in either one or both angular gyri acquired following brain injury (Fisher, 1910). Although this was just the point at which a trend against neurological findings started to set in, Hinshelwood nevertheless reinforced the use of the term word blindness from which point a plethora of other reports of word blindness in adults were put forward.

It was only after a couple of decades later where the term congenital word blindness was found somewhat ambiguous, and it was Orton (1937) who suggested the term "strephosymbolia" (i.e. the twisting of symbols). Orton proposed that the functional specialization of language was deferred in dyslexia such that the requirements needed for learning to read weren't present in order to aid normal development. This was based on Orton's finding where a strong correlation between development delays to other unusual patterns such as "handedness" was made. He further observed increasing numbers of reading and writing related errors to instances where the dyslexics would come across either a single letter or a letter in a word being inverted - letter reversal errors (i.e.

confusing "b" with "d"), and in extreme cases - kinetic reversal errors (i.e. confusing "saw" with "was"), in addition to reading from right to left (due to a reversal of paired letters within a word/sentence), along with a mirroring effect when reading and writing. He suggested that such poor visual perception and representation of letters may have been due to a resulting unstable domination of one cerebral hemisphere over another possibly arising from some form of brain damage. This resulted in Orton to stress the importance of phonetic interpretation, wherein later he proposed the need for multisensory training (having children mark out letters simultaneously while speaking) which he assumed would tap on to the kinesthetic function.

Following the Orton regime, studies into dyslexia continued sporadically as scholars and researchers from various principles began to tackle the problem of reading and spelling deficiencies in dyslexia using newer approaches. The main aim was to identify the features common to a developmental problem in literacy and its observable characteristics within a pool of individuals with dyslexia in a psychological context. It was first brought to everyone’s understanding that the known symptoms of dyslexia (reading, writing and spelling difficulties) were likely to show up all together or in isolation, and also in varying intensity. Furthermore, there was a general consensus at the time where it was thought that dyslexia could be corrected if the appropriate method was used. This prompted several researchers to come forward with various views ranging from psychological, psychiatric to neurological outcomes of dyslexia. This in itself led the researchers into thinking that in order to identify the multifactorial origins of dyslexia, it was of paramount importance to divide potential dyslexic individuals into subgroups based on the type of problem observed (visual, auditory, etc).

The idea of subgroups in dyslexia began to take centre stage when findings related to deficits in auditory (Myklebust & Johnson, 1962) and visual (Ingram, 1970) modalities were first introduced. It was Boder (1973) who then further sub-compartmentalised dyslexia based on the type of spelling errors that was made, namely "dysphonetic" and "dyseidetic". The former was referred to dyslexics who made errors in spelling having far more difficulty with unfamiliar and pseudo-words as a result of poor auditory skills. The latter was referred to dyslexics who made errors in spelling as a result of poor visual skills despite being able to spell regular and pseudo-words relatively with ease. At the same time, certain other observations further added to the tally of subgroups in dyslexia. For instance, one that consists of dyslexic individuals having motor related problems, whilst the largest of subgroups were thought to consist of dyslexics having deficits in both language (e.g. rapid naming in addition to spelling and reading) and motor characteristics (Mattis, French, & Rapin, 1975). Shortly afterwards, a renowned British neurologist by the name of Macdonald Critchley introduced the "specific developmental dyslexia" subgroup which consisted of individuals with dyslexia characterized by pure phonological (speech sounds in language) deficits. Orton’s idea behind multisensory training eventually stimulated the work of both Gillingham (1936), and Gillingham & Stillman (1956), so as to establish linkages between visual, auditory and kinesthetic functions. Once the children were asked to sound out a word aloud, the word was then demonstrated to the children in writing, finally these children were tested to find out whether they were able to mould the word using clay. This technique eventually led to the modern work on the phonological aspects of reading, the method used even to this day in schools known as the "Gillingham-Stillman" method to aid reading, spelling and decoding instructions.

General and educational psychology thereafter began to broaden the outlook on childhood learning difficulties. What seemed initially as impossible when it came to educating CwDys seemed somewhat plausible provided these children had special education that met their needs, i.e. ample time and appropriate management of their reading difficulties. School medical officers and psychologists concerned at the time conducted assessments of children with learning difficulties using intelligence tests, which was all but a trigger immediately following the release of the Warnock Report (1978). By then, dyslexia was considered to be a shortcoming in reading and writing skill, i.e. a specific learning difficulty diagnosed in an event of a difference between the level of reading and chronological age (typically in the range of 17 – 18 months) with the exclusion criteria being low IQ, socioeconomic weaknesses, emotional difficulties, sensory and/or neurological damage. This stance was taken following the definition which was given to dyslexia by the World Federation of Neurology (1968). These exclusionary criteria’s especially in the use of intelligence as a variable to depict the bracket of children who eventually succeeded in getting specialist help sparked a lot of controversy (Applebee, 1971). Not only did it mean excluding those who already had reading difficulties (irrespective of them being either above or below average intellect), most importantly it excluded those who already had reading difficulties in addition one or more factors (e.g. social deprivation, emotional difficulties, etc) due to dyslexia itself. Miles (1983) expressed the importance of overcoming such a caveat in diagnosing dyslexia, where he emphasized the need to group individuals with dyslexia based on a particular set of attributes while dividing them on the basis of others. This meant that not only within group similarities, but also between group differences was more likely to be highlighted. Furthermore, visual errors only explained a small proportion of reading errors, therefore it was quite difficult to characterize the complete range of difficulties experienced by an entire cohort of CwDys.

However, the introduction to information processing of control readers in the early 70’s marked a key transition period which enabled scholars to be more versatile in their approach when identifying deficits in dyslexia. The key to this understanding was the association between speech and phoneme (smallest units of speech sounds that are distinct from other sounds in a given language) awareness, where the difficulties experienced by poor readers' was seen to originate from the language system, especially embedded in the improper exploitation of phonological organization and segmentation. This statement was closely followed by other researchers who advocated the same principle, where it was suggested that any difficulties affecting the process of a given rapid naming task likewise affected speech (Luria, 1974), whilst another study showed how vital it was to possess good phonological awareness in order to learn to read successfully (Mattingly, 1972). Interestingly, it was Naidoo (1972) who first demonstrated that CwDys had more to it than deficits with phonology, since these participants also showed problems related to memory (storage capacity). Although CwDys were slow at object naming tasks, it was found that the vocabulary skill was firmly intact (Denckla & Rudel, 1976). Denckla and Rudel retested the same participant pool using a revised rapid naming task termed rapid automatised naming (RAN) using colours, numbers, objects and letters (a test that’s predominantly used nowadays as a measure of phoneme awareness and reading), still for all yielding the same outcome. With findings of this kind, it became evident that studies into all the language and cognitive skills in relation to reading ability was a prerequisite for both the development of reading and the etiology of dyslexia.

Marshall & Newcombe (1966) proposed three further dyslexic subgroups, namely deep (error in recognition of meaning, i.e. semantics, and the impairment of non-word reading), visual (impaired visual perception), and surface (good understanding of a word's meaning but unable to pronounce it correctly) dyslexia based on the type of deficits that were observed in patients experiencing reading disability due to brain damage. In addition to this, there was another subgroup termed phonological dyslexia, i.e. the poor processing of nonwords with a reduction in the advantage of regular or pseudo-words (Beauvois & Derouesne, 1979). These subgroups were classified based on the most accepted dual-route model of reading (Coltheart, 1980; Warrington & Shallice, 1980) compared to several other competing theories which were present at the time (Morton, 1979). The dual-route comprises of the lexical and the sublexical routes. The lexical route is where an entire word, when presented, specifies the phonological representation of that word, i.e. the entire word is first recognised and then linked to its sound. The sublexical route is one that uses spelling-to-sound (grapheme-to-phoneme) correspondences to pronounce an entire word from a written form (orthography). In other words, the lexical route deals with reading and spelling of words of any kind (e.g. RICE) in the absence of grapheme-to-phoneme correspondences, since words bearing identical spellings are pronounced in a different way (e.g. RICE, DICE). Alternatively, the sublexical route deals with unusual and nonwords having no previously stored representation in the mental lexicon. Since both these routes rely on different strategies (search vs. conversion) to obtain the phonological representation of a printed word, this model was expected to offer a suitable explanation for the observed language problems in dyslexia. In the years that followed, a substantial number of single case studies came up with findings in support of a specific reading and spelling disability in dyslexia tapping on the surface (Castles & Coltheart, 1996; Romani, Ward, & Olson, 1999) and phonological (Snowling, Stackhouse, & Rack, 1986; Vellutino, 1979) dyslexia categories. In addition to these single case studies, came findings from group studies of children with reading problems using the same subcategories (Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996). These group studies focused not just on the pureness of the participant as a phonological or surface dyslexic, but it involved examination of the strengths and limitations of the standard information processing systems. Findings showed a possible impairment either due to a damage to, or partial use of the dual-routes which eventually led Castles & Coltheart (1993) to propose what was an imbalance in either route which gave rise to such impairments in dyslexia. Snowling (1983) claimed a possible degree of preference for dyslexics (phonological and surface) to use either the direct visual route of reading (should the phonological route be impaired) or the phonological route (should the direct visual route be impaired).

The subsequent years marked a remarkable transition of newer theories and findings which extended to other cognitive modalities. Similar to the research on language and reading disabilities, the early studies on perceptual, motor, and attention disabilities was centred on adults with brain injuries. The first ever finding was that of a processing speed deficit demonstrated in a group of CwDys with a strong association between sluggish auditory processing (general words and sounds) and language deficits. For instance, Tomatis (1969) argued that the poor development of language and speech in individuals with dyslexia was a result of an auditory sensory deficit which was thought to be the basis for reading delay. Eye movement study also had a positive impact linking a possible abnormality in the control of saccades to a reading deficit in CwDys (Pavlidis, 1981). Further advances were made by studies which attempted to demarcate the brain based anatomical deficits of CwDys, the first of which produced a strong correlation between an asymmetry present at the parietal-occipital region and verbal IQ (Hier, LeMay, Rosenberg, & Perlo, 1978). This was further followed up by Galaburda & Kemper (1979) in an adult dyslexic who came up with a finding which was opposite to what Hier and colleagues found. It was proposed that the poor reading skills in individuals with dyslexia could be better explained by defective eye convergence and/or unbalanced ocular-motor dominance (Stein & Fowler, 1982). With more and more cognitive psychologists who stepped in, preference was given towards a connectionist model of reading using neural networks (Seidenberg & McClelland, 1989), wherein they were able to conduct simulation studies and cross evaluate their findings to previous real-time data. The study by Nicholson & Fawcett (1990, 2001) provided further in-roads into understanding the vast cohort of deficits, much more than reading and spelling difficulties known at the time. They proposed that due to a prevailing dysfunction in the cerebellum, CwDys exhibited an impaired ability to execute gross and fine motor skills leading up to a chain of other difficulties (poor handwriting, articulatory skills, phonological awareness, and automatization of previously learned tasks and knowledge) which impacted the ability to read and spell accordingly.

Pioneered by the work of Orton (1937) on word-blindness, the early findings of Lovegrove, Bowling, Badcock, & Blackwood (1980) into the magnocellular system (M-system) was a key breakthrough in favour of the visual implications in dyslexia. It was demonstrated that transient visual deficits in dyslexia originated from a damage to the visual pathways in the lateral geniculate nucleus, LGN (Stein & Walsh, 1997). According to Stein (2001), this underdevelopment of the M-system had a clear genetic basis for the poor development of M-cells during brain maturation. Based on the psychophysical studies carried out, the dyslexic individuals in comparison to normal readers were impaired in a wide array of visual processes which tapped particularly on magnocellular processing, some of which included weaker sensitivity towards visual stimuli (Lovegrove et al.,1980), poor ability to observe global movement of visual stimuli (Slaghuis, Twell, & Kingston, 1996) and to detect a moving target when presented against a set of background stimuli (Cornelissen, Richardson, Mason, & Stein, 1995; Cornelissen et al.,1998) when tested via random dot kinematograms. Using more direct means of reading measures and with help of eye tracking, Stein & Walsh (1997) along with Stein & Talcott (1999), proposed the unstable fixations in dyslexic reading may be due to an abnormality in the M-system hampering the precise processing of orthographic information. Stein & Walsh (1997) claimed that these characteristic eye movements (i.e. weakened binocular function) in C&AwDys were caused by an impaired M-system, further explaining why certain individuals perceive text as moving and jittery. Although the latter findings generated some level of controversy over the years (Roach & Hogben, 2004; Steinman, Steinman, & Garzia, 1996), nevertheless it still paved way towards other major visual findings.

Vidyasagar (1999), along with Pammer & Vidyasagar (2005) further demonstrated an important role for visual attention in dyslexia. They suggested the importance of the dorsal stream (as opposed to the ventral stream) of the M-system for efficient operation of the visual "attentional spotlight" or sometimes referred to as the "attentional window". Any shortcomings within the dorsal stream was thought to be significant enough to hinder smooth focusing of the attentional window precisely on orthographic items, a vital function in the pre-lexical stages of word processing. This was based on the understanding that both these streams work hand in hand to accommodate reading, where the dorsal stream assigns attention to precise areas of text thereby offering sufficient responses to the ventral stream to permit close examination of letters (Pammer & Vidyasagar, 2005). The importance of attention in reading was initially documented by Wundt (1924) in control participants testing their ability to reading letters when presented peripherally while maintaining their gaze at the foveal position. He claimed that attention functions to improve perceptual clarity demonstrated by a better detection rate both at the attended (fovea) and unattended (periphery) positions, the performance of the latter being dependent on the distance of the target letter from the centre. Later, studies were conducted with more cluttered multi-element displays to measure the amount of information that a reader could extract at any given time, the term referred to as the perceptual attention span (McConkie & Rayner, 1975).

Moreover, by using visual search tasks in addition to visual cues (which served to manipulate attention), it was shown that visual attention exhibits two functions among others, namely orienting (assist in shifting of the attention focus between visual fields) and focusing (transforms the size of the attention focus) of attention (Posner, 1980). Visual attention was analysed in its ability to filter irrelevant information whilst selecting target information (Eriksen & Schultz, 1979). Attention was then generally viewed as a "filter channel" controlling and aiding information processing from incoming peripheral elements either from the left or right visual field. Visual attention was also analysed in its ability to overcome "crowding" caused by irrelevant information sources (Bouma, 1970). The type of tasks used to test the above properties and functions of attention varied from simple detection of a target (e.g. the appearance of a small gap on a given side of a square), to complex detection and discrimination (e.g. orientation of a titled line among perfectly straight lines) search tasks. Overall, there was a far greater support towards weaknesses in visual attention in dyslexia. Examples include, narrowed perceptual attention span (Lobier, Zoubrinetzky, & Valdois, 2011; McConkie & Rayner, 1975); sluggish engagement and disengagement of attention (Buchholz & Aimola Davies, 2007; Hari, Valta, & Uutela, 1999); problems in maintenance and focusing of attention (Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003; Facoetti, Paganoni, & Lurosso, 2000); problems concerning attention orientation (Buchholz & Aimola Davies, 2005; Facoetti et al., 2006; Roach & Hogben, 2004, 2007); faulty asymmetric hemispheric control of attention (Facoetti & Turatto, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001); inability to inhibit irrelevant peripheral information (Bednarek et al., 2004; Facoetti, Paganoni, & Lurosso, 2000; Roach & Hogben, 2007; Sperling, Lu, Manis, & Seidenberg, 2005); and poor ability in overcoming visual crowding (Bouma, 1973; Martelli, Filippo, Spinelli, & Zoccolotti, 2009). The relevance from these above measures was highlighted behaviourally since the observed performance from such studies was a reliable predictor of reading performance independent of phonological processing between control and dyslexic children/adults (e.g. Facoetti et al., 2006).

In an attempt to narrate this short history of developmental dyslexia, I have tried to fit in as many details as possible to near-absolute completion. However, it must be said that I have restricted my contributions to keep the extract as short as possible. So, one question that remains unanswered is which of these "categories" best explains the probable root cause behind dyslexia? That is certainly the goal of the following section.

1.5 What causes dyslexia?

Over the past couple of decades there has been a vast amount of research into reading acquisition and associated reading difficulties. This has generated a massive amount of literature into developmental psychology which has helped better explain the type of deficits common to individuals with dyslexia, their aetiology, and potential clinical remediation. In an attempt to establish the root cause behind such reading related abnormalities in dyslexia, researchers have come up with multiple theories at various levels of causation – i.e. genetical, neurobiological, environmental, cognitive and behavioural – referred to as the multi deficit model of dyslexia (Bishop & Snowling, 2004; Pennington, 2006).

The earliest of theories into genetics and its involvement in dyslexia came to light in the beginning of the twentieth century when scholars observed atypical reading traits inherited by families spanning several generations (e.g. Hinshelwood, 1907; Rutter, Tizard, Yule, Graham, & Whitmore, 1976). Behavioural genetic studies in twins with known reading problems were then compared to control groups, the outcome which signified a genetic contribution demarcated by roughly 50 - 80% of individual disparity in reading ability (DeFries et al., 1997). This was closely followed by genetic linkage studies in order to locate specific genetic risk loci associated with poor reading. The first of these observations was made in chromosomes 6 and 15 (Cardon et al., 1994) in addition to chromosomes 1 and 2 (Fagerheim et al., 1999), all of which were specific to reading disability in dyslexics. In fact, several other studies have replicated such methods at recent times to demonstrate at least five other regions within the genetic loci (McGrath, Smith, & Pennington, 2006) along with six candidate genes (Kere, 2011) responsible for poor reading in dyslexics. Three other candidate regions for dyslexia were also found on chromosome 18 (Scerri, Paracchini, & Morris, 2010), one of which shared a loci for language impairment (Scerri, Morris, & Buckingham, 2011). Moreover, not all of the heritability accounts purely for dyslexia as most of it taps on to other co-morbid disorders such as ADHD and speech sound disorder, conferring to a lack of gene-specific language retardation in dyslexia (Pennington, 2009).

For a linguistic skill such as reading to function efficiently, it requires the recruitment of certain brain regions to aid processing of oral language, visual object recognition, and establish strong links between the visual and linguistic components (Grigorenko, 2001). However, studies have shown neurobiological evidence concerning a possible brain defect in the causation of dyslexia much of which comes from post-mortem, electrophysiological and functional imaging studies demonstrating both structural as well as irregular activation patterns in certain brain regions. The left hemisphere is regarded to be the main control centre for language functions, and there happens to be various brain regions and neuronal circuitry which are involved in reading such as the anterior, parietotemporal and occipitotemporal areas. The anterior area inclusive of the Broca's area situated in the left inferior frontal gyrus accounts for speech production (phoneme analysis during word identification and articulation of a speech sound while reading). The parietotemporal area (posterior) comprising of the Wernicke's area, superior temporal and angular gyri are mainly in charge of processing speech sounds and conversion of letters to sounds. The occipitotemporal area (posterior) comprises of the Brodmann's area 37 (visual word form area) which functions in the recognition of whole words. The earliest of findings stemming from post-mortem studies in individuals with dyslexia demonstrated a significant structural asymmetry (equal volume on both hemispheres in dyslexics, where in actual fact the volume was considerably larger on the left hemisphere in normal readers), especially in the superior temporal gyrus (a region known as the planum temporale), resulting in poor auditory and language processing in dyslexics (Galaburda, 1992).

Changes to the histological properties of the left-hemisphere perisylvian region have also been reported, in particular the dysplastic nature of enlarged ectopias in individuals with dyslexia, which was thought to result in poor neuronal migration (Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010). Other imaging technologies lent further support to the structural differences previously observed in individuals with dyslexia. For instance, using diffusion tensor imaging, changes in the density of local white matter was observed initially in the left parietotemporal region of the brain both in C&AwDys (Klinberg et al., 2000). A complex study which involved the assessment of functional and structural similarities in a sample of dyslexics speaking three different native languages (English, French and Italian) further demonstrated a startling decrease in the density of gray matter in an area which was previously functionally underactivated - left medal temporal gyrus coupled by a concomitant decrease in the gray matter density within the left frontal and parietal regions (Silani et al., 2005). Pioneered by the latter finding, strong correlations between white plus gray matter integrity and reading skill thereafter became increasingly evident (e.g. Qiu, Tan, Zhou, & Khong, 2008; Shaywitz & Shaywitz, 2005).

Taken together, the causation of dyslexia therefore seems to have direct connections from a genetic perspective to neurobiological factors (especially in brain functioning) which in turn depicts reading skill (Vellutino, Fletcher, & Snowling, 2004). That is, risk genes which interrupt neuronal migration most commonly in the left hemisphere of the dyslexic brain, therein affects the distribution of gray and white matter density within the language-reading network. However, in recent years, studies have demonstrated that the structure and function of the brain eventually ends up being transformed by instruction and length of experience - a typical environmental factor influencing reading skill. For instance, a behavioural study carried out by the help of functional brain imaging comparing individuals with dyslexia across two other control groups, namely chronological-age and reading-age (to test whether group differences contributed to dyslexia) using a visual rhyme task, showed an underactivated left parietotemporal area but not in the occipitotemporal area in the dyslexic group relative to both control groups (Hoeft et al., 2006, 2007). The same was true using a visual sentence comprehension task (Meyler et al., 2007). In another study comparing high risk CwDys with age matched controls on a reading task, the former demonstrated increased bilateral parietotemporal activation on an easy task compared to reduced occipitotemporal activation on a more complex task (Specht et al., 2009). These findings highlight the importance of early prevention and remedial reading strategies (widespread screening for literacy, numeracy and behavioural problems; recurrent evaluation of reading fluency; and providing progressively stronger intervention based on progress) especially in CwDys (Fletcher & Vaughn, 2009; Samuelsson et al., 2007).

With all of the aforementioned taken together, it is evident that not a single aetiological factor on its own is capable enough to cause dyslexia during brain development. In fact, the phenotypic indicators for dyslexia are the end result of a complex interaction between apparent risk factors with respect to each and every level of explanation as stated by the multi-deficit model of dyslexia. Given the amount of time that's elapsed since these initial findings were first brought to light, there has been a significant outburst of theories and studies which have been proposed to explain both the cognitive and behavioural manifestations of dyslexia each with its varying degrees of strength and limitations. These theories, possibly expressed as secondary causes of dyslexia, are classified under five main categories, namely phonological, cerebellar, auditory, and visual processing. The next section explains the relative causes of dyslexia along with individual findings backed by contending evidence, both in support and against the current framework of dyslexia. Note that, the ever expanding literature on dyslexia research has paved way to several versions with respect to each theory, reason why it is impossible to represent everything in detail. Instead, the currently most well-known description to best describe each theory of dyslexia is reported.

1.5.1 Phonological Deficit Theory

Before we proceed any further into more technical aspects of this theory, it is worth reminding ourselves why individuals with dyslexia find reading to be far more difficult. The phonological model is central to the understanding of dyslexia since it's a key element within the language system and it functions independently from hierarchical cognitive and linguistic functions (e.g. intelligence). The ability in learning to read is an age old process unlike speaking which is thought to be much more of a habitual process occurring at a pre-attentive state. Although reading fluency in children is improved with appropriate early age instruction, the biological pathway that governs this process needs special mention. English, being a universally spoken language, is phonemically complicated in that it is comprised with 26 letters of the alphabet which creates up to 44 potential sounds by incorporating roughly 70 combinatory letters. For instance, the word "cat" contains three phonemes, namely /k/, /æ/, and /t/, but in actual fact a person listening to this would hear it as one complete word, "cat", rather than three separate sounds. When this word (cat) is spoken, the three separate sounds get merged together to produce one word. But when it comes to reading, one has to be aware that there are three sounds which govern this one word. Therefore, learning to write requires the need to break down the constituent syllables of a particular word into unique smaller speech sound segments (phonemes) symbolised by a combination of few letters (grapheme). However, in learning to read, especially when it comes to nonwords, the reader should be first able to visually recognise letter shapes, the particular order in which they appear and the visual word form they are most likely to represent (orthography). The next most crucial process is to depict the meaning (semantics) of this particular word rapidly, automatically and accurately, and for this to happen, the graphemes have to be linked with its corresponding phonemes (grapheme-to-phoneme correspondence). Unlike with nonwords, for familiar words, the initial orthographic stage retrieves the meaning from previously stored representations in the lexicon within the semantic memory, the process which is backed by the phonology-to-semantics loop within the language system. Therefore, an individual's working knowledge of the phonological sound structure of speech (phonemic/phonological awareness) is a prerequisite, as it then predicts how good the grapheme-to-phoneme correspondence is for the normal development of reading ability.

The phonological theory is said to be one of the most influential indicators of dyslexia which has gained a huge interest among many other areas of dyslexia research. Theorists have taken two stances when it comes to describing the nature of phonological deficits studied from dyslexic individuals (**figure 2**). At the neurological level, reports from both the anatomical (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985) and functional imaging (Shaywitz et al., 2002) studies suggest that the foundation of the phonological problem is a resultant congenital dysfunction of the left hemisphere perisylvian brain areas, which is thought to hinder either the development of phonological representations and/or the connectivity linking both the phonological and orthographic representations. Meanwhile, others theorists proposed a deficit at the cognitive level, i.e. within the language system, which further manifests in a direct behavioural problem. The reading and spelling problems encountered by individuals with dyslexia was thought to be an underlying phonological impairment, i.e. an inability to break down a spoken word into constituent phonemes such that they are unable to develop the necessary grapheme-to-phoneme correspondence, all this despite an intact semantic system (Frith, 1997; Griffiths & Snowling, 2002; Snowling, 1981). Support in favour of the phonological theory comes from studies carried out largely in a population of normal readers, the findings which were then compared to individuals with dyslexia matched for age and IQ. In such a setting, the phonological awareness of an individual is thought to be a good predictor of reading ability. Studies in fact have shown poor performances demonstrated by dyslexic individuals in tasks requiring phonological awareness, e.g. naming speed (Rapid Automatised Naming – RAN, i.e. the retrieval and naming of digits, objects or colours in a rapid fashion: Torgesen, 1999) and nonword repetition (Pennington, Van Orden, Smith, Green, & Haith, 1990). Moreover, phonological deficits have been previously pointed out in individuals with dyslexia having demonstrated poor performances in slow automatic naming, verbal short term and working memory (temporary storage), these deficits possibly arising due to difficulties associated in the storage and retrieval of unique orthographic representations, along with shortcomings in the information processing pathway (Snowling, 2000). Studies which offered pre-training of phonological awareness skills to both the dyslexic and control groups has enabled the dyslexic group to improve their standards of reading significantly (Castles & Coltheart, 2004), which further goes to show the importance of early reading instruction.

Figure 2: Proposed cause of dyslexia according to the phonological deficit theory. Any genetic abnormality during the brain maturation stage results in changes which affects both the asymmetricity of the planum temporale (which covers a part of the Wernicke’s speech area) and the regularity of the perisylvian region. This is then thought to affect the phonological language system at a more cognitive level, the effect which can certainly be minimized using appropriate remediation strategies. Any shortcoming in phonological processing therein hinders the conversion of grapheme-to-phonemes which leads to poor spelling and reading, in addition to a weak phonological awareness (inclusive of a phonological deficit). A phonological deficit alone is thought to result in an impaired short-term memory and naming skills at a behavioural level. [Source: Frith (1997)]

While studies have demonstrated such strong links between reading ability and phonological skill, critics have argued whether such phonological deficits were actually a causal deficit or one that was influenced by an external third party. Supporters of the phonological deficit theory casted doubts over initial findings with respect to the phonological deficits observed in dyslexic populations thought to be a result of co-occurring visual difficulties. For instance, a study by Ellis (1981) carried out between controls and CwDys in a task required both groups to make appropriate judgements when matching letters that were ether similar or different. Findings from this study showed that, compared to the control group, the speed of matching judgements by the dyslexic group were far slower in tasks which tested for name encoding skills (e.g. Xz and Xz) unlike that for letter pairs which were visually similar (e.g. XX and zz). Another study by Elbro & Jensen (2005) tested a group of dyslexic and normal reading children on the ability to form phonological representations of lexical items, i.e. pseudo-names and known words, using a single word decoding task. Findings showed that, compared to the dyslexic group, the reading age controls had the better of nonword reading and phoneme awareness tasks. Although, both the groups showed equal ability to rapidly learn to associate familiar names with images of people, the time taken in learning to relate a list of pseudo-names with pictures were far too long in the dyslexic group. When the procedure was repeated using long familiar words, the dyslexic group demonstrated a shorter learning period compared to controls in the imitation task. All of these findings suggest the weakly specified phonological representations to be a fundamental problem in dyslexia independent of visual difficulties. Further support for an underspecified phonological representation, rather than an analytical problem, comes from a large array of studies (e.g. Boada & Pennington, 2006; Snowling & Hulme, 1989).

There have also been quite a few cases of dyslexic individuals reported to have demonstrated intact phonological skill (e.g. Curtin, Manis, & Seidenberg, 2001; Valdois et al., 2003). For instance, scholars have looked at potential speech perception deficits in dyslexia to be an area of concern when associating it with the weaker phonological awareness skills. Clinical observations in the past have mentioned possible word finding difficulties (i.e. despite being able to select correct word/s by the help of a reference/cue, it is the inability to construct a target word independently which then leads to behaviours including repetitions, omissions, substitutions, insertions and delays) within a child dyslexia population (e.g. Messer & Dockrell, 2006; Snowling, Wagtendonl, & Strafford, 1988). Similarly, studies providing a measure of pronunciation accuracy have demonstrated findings consistent with the argument that the phonological representations may have been omitted (Elbro, Borstrom, & Petersen, 1998). However, upon replication of

Elbro and colleagues study, Fowler & Swainson (2004) claimed that the group differences were of a significantly smaller margin and this was the case only in a few of their experimental measures, suggesting that these results may have been due to a developmental co-morbidity between dyslexia, specific language impairment, speech sound disorder, or a resultant delay in speech. In response to this finding, a study carried out a few years earlier by Joanisse, Manis, Keating, & Seidenberg (2000) examined how three subgroups of CwDys (phonological dyslexics, developmentally language impaired and delayed-type dyslexics) performed in a task which demanded good language and reading skills. Both phonological dyslexics and developmentally language impaired individuals demonstrated identical below par reading patterns indicative of poor phonological skills. More importantly, a clear speech perception deficit was observed in both the language impaired and delayed-type dyslexics, whilst a phonological impairment was also evident in children whose speech perception was normal. Given the language skills of normal children showed a close resemblance to the delayed-type dyslexics, it was concluded that a related reading deficit may have been solely due to a general delay in reading than a phonological impairment.

Findings from several behavioural studies indicate dyslexic individuals with phonological deficits to also have poor verbal short-term memory (Baddeley, 1986) and working memory (Swanson, 1994) due to ineffective phonological coding (Snowling, 2001; Vellutino et al., 2004). Within the working memory, of interest was a particular impairment which was found to occur within the central executive (Beneventi, Tonnessen, Ersland, & Hugdahl, 2010; Reiter, Tucha, & Lange, 2005; Sela, Izzetoglu, Izzetoglu, & Onaral, 2012), the control centre thought to be in charge with modulation of the articulatory loop and visuo-spatial sketchpad (specialised for short-term storage and manipulation of spatial and visual information, Baddeley, 2003), information retrieval (from long-term memory) and integration of storage capacities, the latter two functions thought to be further supported by another component referred to as the episodic buffer (specialised for short-term storage with an ability to merge various types of information to form a given episode, Baddeley & Jarrold, 2007). Also, it assists in coordination of attention functions, namely attention focusing and exclusion of irrelevant stimuli (Baddeley, Gathercole, & Papagno, 1998), splitting of attention (Baddeley, Chincotta, & Adlam, 2001), and switching of attention between peripheral visual fields (Baddeley, Baddeley, Wilcock, & Bucks, 2001) towards incoming verbal and visual information. Therefore, any short comings with the central executive or associated components could result in an impairment of visuo-spatial attention, further hampering language comprehension and reading. For instance, it was reported that an impaired central execute function resulted in individuals with ADHD to perform poorly in tasks which required exclusion of irrelevant stimuli (Gathercole & Alloway, 2006). Individuals with lower span have also demonstrated inattentiveness with a greater tendency to be forgetful with regards to the study instructions given to the participants before conducting a certain task, which lead them into overcomplicating the task assigned to them (Gathercole, Alloway, Willis, & Adams, 2006; Gathercole et al., 2008). In essence, the difficulty experienced by such a group of individuals came down to a poor ability in focusing and switching attention, in addition to problems concerned with assimilating information coming from neighbouring components of the working memory. Moreover, some scholars suggested that reduced visual attention span in dyslexic individuals was connected to a limited processing resource effect, i.e. difficulty in maintaining information in the working memory, evident only when the experimental procedure requires a higher memory load, thus further affecting reading ability (Beneventi, Tonnessen, Ersland, & Hugdahl, 2010; Swanson & Sachse-Lee, 2001).

When considering the adult dyslexic population, studies claim that despite phonological skills being intact, the problem may potentially be in the ability to gain access to these phonological representations. This claim was based on a comprehensive sequence of studies carried out within AwDys in addition to in-depth review of the cognitive dyslexia literature (Ramus et al., 2003; Ramus & Szenkovits, 2008). Phonological short-term memory is considered to play a highly important role in forming sound based representations of written text, i.e. converging both the graphemes and phonemes of a word segment while holding on to the remaining segment within the memory. Ramus & Szenkovits (2008) favoured the use of simple rhyme judgement tasks to investigate the exact nature of short-term memory deficits between AwDys and control groups on a task requiring participants to differentiate two nonword sequences, one which rhymed but differing by just a single phonetic element (e.g. "jaz" and "jaʒ"), and the other with non-rhyming nonwords (e.g. "taz" and "bam"). Compared to controls, AwDys were significantly affected when differentiating between both word sequences. Although dyslexics demonstrated a phonological similarity effect just as the control group did, the performance for AwDys gradually improved parallel to that of controls as the phonological similarity reduced. This evidence was sufficiently enough for the authors to claim that phonological representations were perfectly intact in AwDys, and should that be not the case, they insisted that dyslexic individuals should have exhibited a higher phonological similarity effect than controls. Hence, it was proposed that the phonological difficulties in dyslexia were due to a defect in the short-term memory processes regulating phonological representations, and certainly not a direct phonological deficit *per se*. Furthermore, the study by Boets & colleagues (2013) also supported the view of Ramus & Szenkovits

(2008) by presenting neural evidence linking dyslexia to intact phonological representations (similar to that of skilled readers) with poor accessibility for efficient higher-order phonological processing. The findings from both these studies clearly oppose the principal view held by proponents of the phonological theory, but it must be said that a majority of studies (especially electrophysiological and speech-perception types) have demonstrated degraded phonological representations within the child population, inclusive of both CwDys and pre-readers with a possibility of undetected dyslexia. Moreover, the controversy over the past decade or so concerning the exact source reflecting impaired speech processing in dyslexia have been circulating around both input (e.g. Ramus, 2001; Szenkovits & Ramus, 2005) and output (e.g. McCrory, Mechelli, Frith, & Price, 2005; Szenkovits & Ramus, 2005) processes, although a definite locus is yet to be identified on a consistent basis. Nonetheless, proponents of the phonological deficit theory remain firm in their stance claiming phonological deficits to be the sole cause of dyslexia.

1.5.2 Double Deficit Theory

Although the phonological deficit theory has the advantage of offering a logical framework for developmental dyslexia, there are scholars who still do not believe with absolute conviction that it really is the case. Opponents of the phonological deficit theory point out that reading disability and associated cognitive deficits (e.g. poor name retrieval) in dyslexia have nothing to do with the limitations of phonological coding and working memory (e.g. Wolf & Bowers, 1999; Wolf, Miller, & Donnelly, 2000). Instead, they hypothesize the presence of three independent sources of reading disability in dyslexic individuals, namely (i) a phonological deficit interrupting phonological awareness; (ii) the sluggishness in naming speed interrupting both orthographic processing and reading fluency; and (iii) discrepancy integrating both the phonological and rapid automatised naming (RAN) deficits, referred to as the double deficit (Katzir, Kim, Wolf, Morris, & Lovett, 2008; Miller et al., 2006). Supporters of the double deficit theory purport that a rapid naming speed requires an assembly of phonological, semantic, perceptual, conceptual, attentional, motor and memory assisted sub-processes, thereby highlighting the importance of accuracy and rapid processing times (automatization) within these functional units (Wolf, Bowers, & Biddle, 2000). Any disruption to the timing mechanism was thought to negatively influence the accuracy in the lexical-phonological word representations resulting in a redundant capacity to store representations of word specific spellings, i.e. a rapid naming deficiency. This finding dominated most of the literature on RAN deficits in dyslexia both within a language (regular or transparent orthography, e.g.

Landerl, 2001) and non-linguistic (digit, object and colour naming, e.g. Manis, Doi, & Bhadha, 2000) mediums. In both cases, significant group differences between controls and dyslexic individuals were reported when the stimuli presented consecutively was separated by a short time span, with group differences levelling out when presented at longer time spans (e.g. Goswami et al., 2002). RAN also happens to be a better predictor of reading fluency especially with previous studies reporting of increased likelihood for both RAN and reading to influence the speed at which phonological representations gets fetched from the long-term memory store (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). Furthermore, some scholars using longitudinal studies have further elucidated this processing speed deficit to predict reading acquisition at later stages of development (Landerl & Wimmer, 2008). Any early disruption to the quality of the connections at brain areas concerned with retrieval (left mid-fusiform) and/or production of names (anterior-fusiform) was thought to limit the capacity in learning to read over time, eventually portraying whether an individual is a single or a double deficit reader (Cronin, 2011).

Nevertheless, the findings generated in support of the double deficit theory (phonological and RAN) are somewhat unclear. While some reject this theory due to the inconsistent findings (e.g. Chiappe, Siegel, & Wade, 2002, Chiappe, Stringer, Siegel, & Stanovich, 2002; Lesaux & Siegel, 2003; Vukovic, Lesaux, & Siegel, 2003), whilst others do so based on interpretive (e.g. Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002) and methodological grounds (e.g. Compton, DeFries, & Olson, 2001; Vaessen, Gerretsen, & Blomert, 2009; Furnes & Samuelsson, 2011; Vellutino & Fletcher, 2005; Vukovic & Siegel, 2006). Moreover, these sorts of inconsistencies seen to arise from the aforementioned studies could eventually come down to the type of orthography being used. Assessing language and cognitive skills to successfully predict reading acquisition have produced varying findings in transparent orthographies (e.g. Norwegian) compared to an opaque orthography such as English (e.g. Caravolas, 2005; Lervag & Hulme, 2010), hence raising doubts when generalizing early literacy development across varying alphabetic systems (Share, 2008). However, findings from some recent studies using various orthographies have lent some support towards the double deficit theory (e.g. Katzir et al., 2006, 2008; Torppa et al., 2013). For example, in Katzir et al (2008) study, having tested a large group of poor English reading children (restricted to the second and third grade), the findings from their study displayed all three deficit subtypes at different levels of reading. In the word level, poor performance on all word reading measures indicated a possible impairment in the rapid retrieval of phonological codes. More importantly, this double deficit was significantly worse in individuals with dyslexia compared to control readers (similar to those found in Jones Jones, Branigan, Hatzidaki, & Obregon, 2010; Branigan, & Kelly, 2009; and Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007). This finding of a poor RAN performance in addition to outwardly observable problems (e.g. stammering) suggests speech that is not grammatically well formed to reflect more complex difficulties than phonological code retrieval itself (Katzir et al., 2008). This prompted Katzir and colleagues to suggest a possible impairment in either skill automatisation and/or temporal processing, i.e. a processing deficit concerned with rapid serially presented stimuli and associated sub-processes, possibly further resulting in a limitation in the available resources needed for the reading task. Despite these positive findings, the discrepancy in reading ability present within the double-deficit literature and the unclassified correlation of RAN to a particular facet of the reading process have undoubtedly resulted in a lack of precision regarding slow naming and its specific role in reading ability.

Nevertheless, in accordance to the double deficit view of dyslexia, certain studies have also shown difficulties in processing multi-letter strings within the dyslexic population to reflect deficits with both phonology and visual span (e.g. Bednarek et al., 2004; Hawelka & Wimmer, 2005; Pammer & Vidyasagar, 2005), the latter being an attention component of reading. The roles of both phonology and visual span in reading was emphasised initially using the multi-trace model - MTM (Laberge & Samuels, 1974) whereby two forms of word reading was postulated, namely global and analytic. Visual span refers to one particular region of a given peripheral visual field where information is selectively extracted with each and every fixation. Within a large visual span, chances are that there will be more resourceful visual search (a task which requires searching for a suitable target among a variable number of competing distractor items) performances. In essence, a wider visual span would allow more visual information to be processed during each fixation, concomitant with lesser fixations necessary to execute efficient visual search. This process is known to be aided by visual attention extending over a given target word (global reading mode) closely followed by narrowing down the attention focus to specific segments within the text (analytic reading mode). Both these processes vary from phonological processing in that, the output with respect to latter is either generated by individual analysis of focused elements (analytic) or via a solitary step (global). In the case of dyslexic individuals, a series of studies by Valdois and colleagues have shown impaired letter and symbol strings. For instance, Valdois et al (2003) carried out a case study consisting of two French CwDys, participant X demonstrated difficulties in irregular and nonword reading and nonword spelling (i.e. phonological dyslexia profile), while participant Y with just irregular word reading difficulty (i.e. surface dyslexia profile). It was reported that participant X went on to demonstrate significant phonological impairments (having performed well below the chronological and reading aged matched controls) while participant Y demonstrated normal phonological awareness (having performed well above the chronological age-matched controls). Based on the attention tasks carried out (consisting of a whole and partial report task requiring both participants to identify a cued letter within a random string of five letters), unlike the phonological dyslexic, the surface dyslexic was severely poor during the whole report, in addition to when reporting the last two letters during the partial report. This prompted the authors to suggest dissociations between both the phonological and visual attentional deficits in reading.

Similar findings were reported from follow-up studies (e.g. Bosse, Tainturier, & Valdois, 2007; Bosse & Valdois, 2009; Peyrin et al., 2012; Prado, Dubois, & Valdois, 2007). Interestingly, these authors went on to propose that deficits in visual span had no links with problems with phonology, further purporting the likelihood of different dyslexic subtypes (e.g. Bosse, Tainturier, & Valdois, 2007; Lallier, Donnadieu, & Valdois, 2010; Lassus-Sangosse, N'Guyen-Morel, & Valdois, 2008; Valdois, Lassus-Sangosse, & Lobier, 2012). For instance, Bosse et al (2007) indicated the presence of four subgroups of dyslexic participants based on the impairments that was evident (phonological awareness, visual attention span, both phonological awareness and visual attention span, and those without any impairments), suggesting that reading disorders can be a result of any one or a combination of both types. Using a larger test battery carried out within a population of typically developing (first, third and fifth grade) children, visual attention span was reported to be a strong predictor of (irregular word) reading completely separate from that of phonological awareness (Bosse & Valdois, 2009), which goes to indicate the importance of attention span when arbitrating lexical analysis during early reading. Further supporting evidence of single and double deficits came from Lassus-Sangosse et al (2008) where it was reported that CwDys was free of any impairments towards letter strings when presented serially, compared to stimuli when presented concurrently (visual attention span reduction), with similar findings also reported to be observed in an AwDys possessing a phonological dyslexic profile (Lallier et al., 2010). Interestingly, the latter reported this particular AwDys to have also showed deficits in shifting attention, both in the visual and auditory modalities (i.e. rapid sequential deficits), despite possessing normal visual attention span. The latter two studies taken together goes to show that specific modal shortcomings are prominent despite intact phonological processing (Lassus-Sangosse et al., 2008), with specific amodal impairments possibly involving phonological difficulties (Lallier et al., 2010). Furthermore, Peyrin et al (2012) confirmed both subtypes (phonological and attention span) to be associated with separate neurobiological factors using fMRI, i.e. impaired phonological awareness with intact visual attention span corresponding to reduced left inferior frontal gyrus activation, and impaired visual span with normal phonological awareness corresponding to reduced parietal lobule activation (during a phonological rhyme judgment task vs. visual characterisation task). Evidence from eye tracking studies further added to the tally of double dissociations (e.g. Hawelka & Wimmer, 2005; Prado, Dubois, & Valdois, 2007).

Nevertheless, some proponents of the phonological theory have scrutinised the collective involvement of a core visual attention span deficit based on the methodology employed. For instance, the whole and partial report tasks utilised by Bosse et al (2007) was criticised as it was thought that the difficulty was actually due to an impairment in switching the information from a visual mode to a verbal retort, rather than an impairment to do with visual attention span. This argument was based on the idea that both controls and individuals with reading disorders were not expected to demonstrate any impairment when assessed on a visual attention task consisting of non-verbal stimuli (e.g. Collis, Kohnen, & Kinoshita, 2013; Hawelka & Wimmer 2006; Lassus-Sangosse et al., 2008; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). However, studies comparing standardised visual span (consisting of linguistic stimuli) with a symbol span task (same idea as the visual span task, just this time symbols were used as the stimuli rather than letters) have reported poor performance by participants with dyslexia for visual span tasks compared to the symbol span task. It is without doubt that the standardised span task involved higher cognitive demands, consistent with that idea of increased memory span in tasks involving linguistic stimuli as previously demonstrated by Pelli, Burns, Farell, & Moore-Page (2006). Other studies which demonstrated the significance of a core visual attention span deficit comes from investigating both children (Pammer, Lavis, Hansen, & Cornelissen, 2004) and adult (Jones, Branigan, & Kelly, 2009) dyslexics on symbol search vs. visual search tasks. The symbol search task consisted of five symbol strings followed by two response options (correct option - identical string to the one viewed previously, whilst incorrect option - identical but fresh symbol string), with the visual task being similar in both with the exception of the stimulus type. By having participants to select an appropriate option based on the specific string presented to them, the authors reported an identical pattern of findings from both studies with dyslexics being significantly impaired (compared to controls) on the nonverbal tasks. The aforementioned studies (Jones, Branigan, & Kelly, 2009; Pammer et al., 2004) taken together indicates a visual attention span deficit reflected by a shortcoming which was totally specific, rather than it being a result of, a broad-spectrum phonological deficit. Interestingly, based on the findings by Ziegler et al (2010), it was concluded that the core difficulty in double deficits associated with dyslexia comes down to identification of digits and letters, unlike symbols, since the former undergoes phonological mapping with the difficulty thought to be residing within the process itself. However, a recent finding made by Romani, Tsouknida, di Betta, & Olson (2011) overruled Ziegler et al's (2010) claim having later reported of a deficit associated with symbol matching (in the absence of any verbal naming) in individuals with dyslexia compared to their control counterparts. When considering the aforementioned studies (in addition to Dubois et al., 2010; Valdois, Lassus-Sangosse, & Lobier, 2012), there is evidence against a core phonological basis in double deficits involving visual attention.

To recap…

What we have seen from both the phonological and double deficit theories is that, what was once thought of as a pure phonological deficit (i.e. impairment within the phonological loop and surrounding components of the language system), is now seen to extend pretty much in all aspects of the memory component to a point where even an attentional component is thought to be a potential contender. At this juncture, it is also worth reiterating that RAN tasks (especially those using letter stimuli) involves a multifaceted assembly of sub-processes ranging from attention, detection of word features, establishment of orthographic representations, combinatorial analysis of visual-phonological information, and articulation, with key emphasis being precise timing of reading system. Nevertheless, it is quite a complex task to define contributions for each of these functional components, which would otherwise help determine the reasons for which individuals with dyslexia are poor performers in order to better understand the fundamental short comings in reading fluency. In this regard, alternative theories in the cause of dyslexia, particularly those with advance lower-level sensorimotor impairments, focuses more on fundamental and less specific causes of reading disability independent from word and sentence level influences. Some of these theories concentrate specifically on aspects of skill automatisation, auditory and visual perception. In line with the above suggestion purporting deficits in the processing resources is the theory of a skill automatization deficit in dyslexia, which shall be dealt next. I strongly believe this shall complement the aforementioned rapid automatisation deficit in dyslexia, despite the two different functional modalities.

1.5.3 Dyslexia Automatization Deficit Theory

Most research has weighted a lot of interest in language-related tasks, particularly that of reading, in order to deduce the deficits underlying dyslexia. Reading is not a skill which just develops over time (compared to language acquisition), rather it is a process which requires an investment of considerable time and effort (i.e. skill acquisition) on the part of the reader. Studies in the past have described two models of reading skill acquisition, namely Anderson's acquisition of expertise (Anderson, 1982) and Logan’s instance theory of skill acquisition (Logan, 1988). Anderson proposes two main stages present in the acquisition process, that is, knowledge compilation and production tuning. Knowledge compilation signifies the acquirement of a declarative knowledge (knowledge pertaining to a linguistic form, e.g. that "A" is the first of 26 alphabets) so as to know that "something is actually the case". This is then followed by proceduralization of that knowledge (i.e. conversion of knowledge of a declarative form to routine production) so as to identify "how exactly to complete the goal". The production tuning in this regard denotes the selection of a particular rule to a given task. This theory of learning was applied to a range of cognitive skills (e.g. letter recognition) in addition to motor related tasks, as we will see later (e.g. Fitts & Posner, 1967; Poldrack et al., 2005). According to Logan’s instance theory of skill acquisition, the reader commences the process of learning to read by initially following the basic rules of articulation (e.g. for "c" preceding "e", the corresponding phoneme sounded out as "/s/"). Whenever the learner recognizes a syllable or word, such rules then become applied which then gets represented in the memory as a particular "instance". Every time the reader performs such operations, these so called "instance chunks" become gradually hardwired in the long-term memory. There comes a time where the reader would be then able to retrieve the best copy of a previously stored instance, both rapidly and effortlessly, rather than having to apply any rules. When considering this feat with children who are yet to acquire fluent reading, their reading is generally thought to be non-automatic by default, as such individuals finding it hard to pronounce written words along with a poor ability to read rapidly (Denckla & Rudel, 1976). This condition is far worse in dyslexic individuals having failed to learn to read well in spite of reading instruction. The dyslexia automatization deficit (DAD) theory points toward a general problem in the automatization of skills rather than it being a primary deficit in the phonological, auditory, and/or visual modality (Nicolson & Fawcett, 1990).

Failure to attain a required range of skills at an automatic, as opposed to conscious, level of control eventually determines the type of demands that are being exerted. A previous account featuring the influence of attention on two cognitive processes, namely controlled and automatic, was linked closely with learning (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). The controlled processes are voluntary in nature, entailing attention, of which the resulting processing speeds are normally on the slower side, whilst the automatic processes are regarded to be rapid acting independently of attentional demands. As described by Shiffrin & Schneider, "Automatic processing is well learnt in long-term memory, it’s demanding of attention only when a target is presented, it’s parallel in nature, it’s difficult to alter, to ignore or to suppress once learned, and is virtually unaffected by load" (1977, p. 127). Studies in the past have utilized many tasks to analyse how closely both these modes of attention was related to automaticity. One of the earliest well-known tasks to be carried out was the Stroop task (Stroop, 1935). The Stroop task demonstrates the capacity to which an individual is able to allocate attention to a subset of cognitive demands whilst allowing a proportion of the remaining process to proceed free of any attentional control. The observed Stroop interference effect signified a direct link between interference and reading skill in dyslexic individuals, exemplified by a fundamental deficit in attention allocation when manipulated by spatial context and task demands. That is, in tasks requiring participants to read words whilst ignoring the font colour (e.g. XXXXX vs. GREEN, compared to XXXXX vs. GREEN), dyslexics were unable to efficiently ignore certain stimulus features in the expense of others (Helland & Asbjornsen, 2000; Kelly, Best, & Kirk, 1989; MacLeod, 1991). Studies carried out using individuals with ADHD (excluding those known to have reading difficulties) also reported of pure attention deficits which hindered reading, a task generally demanding a greater capacity to sustain and shift attention essential for efficient reading (Savitz & Jansen, 2003). Furthermore, many follow up studies in CwDys generated findings attributing phonological difficulties on the basis of poor automatisation, rather than a difficulty in handling phonological tasks (e.g. Faccioli, Peru, Rubini, & Tassinari, 2008; Kapoula et al., 2010; Protopapas, Archonti, & Skaloumbakas, 2007). These authors suggested that the Stroop interference task actively demanding sustained attention and the capacity to inhibit are both scarce in dyslexics, devoid of difficulties in mental flexibility (but see Moores, Nicolson & Fawcett, 2003[1]). On the whole, all three of these studies concluded that any interference in word reading would clearly result in poor reading ability, since both the reading and the Stroop interference have similar processes tapping on to executive functions (e.g. stimulus inhibition and sustained attention) thereby playing an important role in skill automatisation.

Studies have also concentrated at motor skill, particularly that of postural control, to be exclusively related with automaticity. Postural control entails a combination of sensory information coming from visual, vestibular and proprioceptive sources so as to facilitate the assembly of motor commands to maintain the body at a precise position. The body's

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[1] A study carried out by Moores, Nicolson and Fawcett (2003) between a group of CwDys and age matched controls, investigated both the attentional and automatisation abilities using a focus/shift attention paradigm. The findings from this study demonstrated standard processing of attention with regards to sustaining attention and attention switching. However, the dyslexic children demonstrated a weaker ability to identify a number of different shapes in an automatic fashion. Despite the use of an entirely different paradigm with the finding of a normal sustained attention so different to that obtained from Stroop tasks, the results from this study did offer support towards the DAD theory (Nicolson & Fawcett, 1990).

posture is in full control given the availability of attentional resources, which also happens to be distributed among several other tasks performed simultaneously. The well known support for DAD comes from the study of Nicolson & Fawcett (1990) assessing postural stability in a group of individuals with dyslexia. They used this method for identifying processes as being automatic or controlled based upon an individual's attention capacity. The authors reported the constant need for CwDys to devote extra attentional resources especially when controlling their balance (primary task) whilst executing concurrent dual tasks (auditory choice - easy task, and backward counting - hard task), a term they referred to as conscious compensation. To further test the limits to which the dyslexic individuals were able to compensate for additional attention resources and the severity of automatization, Nicolson & Fawcett (1994) measured basic aspects of phonological, speed processing and motor skills using a large test battery (**figure 3**). Nicolson & Fawcett (1995) interpreted findings observed from the dyslexic group to be a deficit in being unable to fully automatize the required skills needed, since they were expected to invest more attentional resources so as to control their balance in dual tasks unlike in the lesser demanding tasks. In doing so, these resources which enable them to carry out a secondary task would be under conscious, rather than automatic processing.

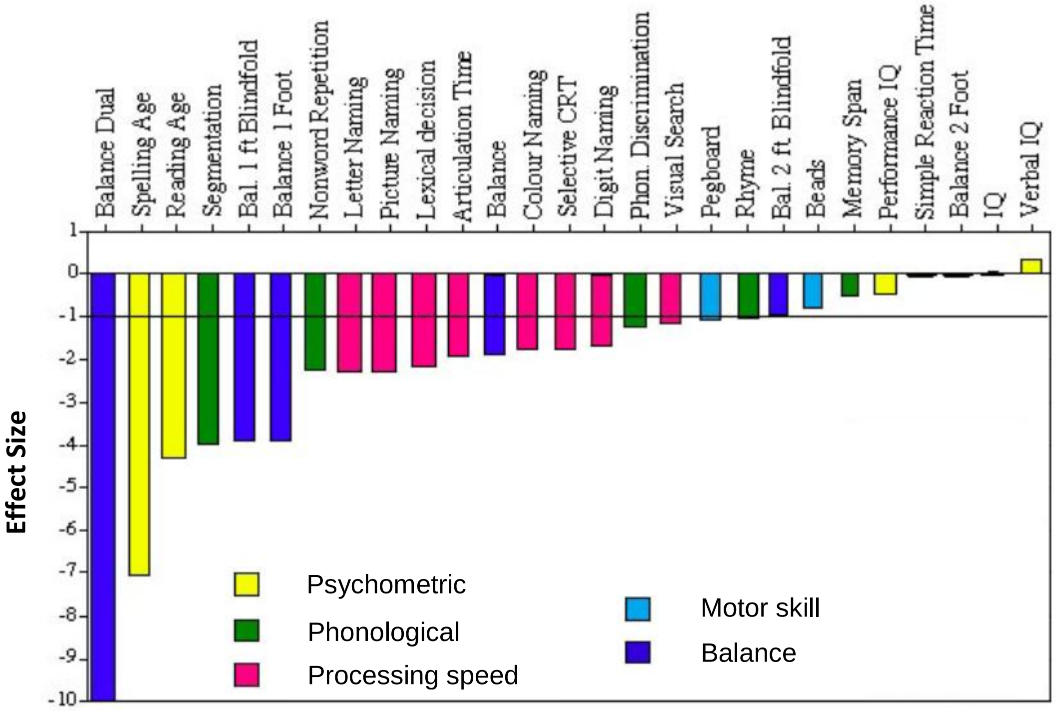

Figure 3: Bar graph portraying the deficits found in a battery of cognitive, motor and linguistic tests. The effect size indicates the relative degree of impairment within each experimental measure. [Source: Adapted from Nicolson & Fawcett (1994)].

Nicolson & Fawcett (1995) proposed the difficulty of motor skill automatization in dyslexic individuals may closely be associated with phonological deficits, given the latter develops in a similar manner (i.e. without precise instruction). However, there seemed to have been some level of methodological biasness. First, DAD is clearly obvious when dyslexics were required to perform more than one skill simultaneously. Based on subjective evidence, it has been previously demonstrated that dyslexic individuals showed intense levels of fatigueness following the completion of a task (Augur, 1985; Ryden, 1989). Given the increased demand for something strenuous as conscious compensation, it is hardly surprising that dyslexic individuals have an overall weaker task performance. Second, although findings from their study were closely attributed to conscious compensation, however, not a single theory was entirely supported as the observed deficits were not restricted to a particular skill (phonology, processing speed or motor). A question which arose was the type of cause(s) underling such a range of diverse difficulties. Third, although DAD theory provided a good account of a vast array of dyslexic symptoms, however, it did not provide an underlying neurological substrate so as to explain why CwDys have problems in skill automatisation. In the next section we shall see how the cerebellar deficit theory at a brain level challenges to tackle these areas.

1.5.4 Cerebellar Deficit Theory

The cerebellum is considered to be the brain’s auto-navigator which functions by precisely anticipating and pre-planning the timing of muscle contractions in an automatic fashion, coordination of smooth timely movements thereby ensuring optimum motor performance (Stoodley & Stein, 2011). The first study investigating the potential involvement of a cerebellar deficit (CD) in dyslexia was that of Leiner and colleagues who pointed out that the lateral cerebral hemispheres had established links far as the frontal cortex (e.g. Broca’s area for language), a finding central to both language acquisition and skill automatisation (Leiner, Leiner, & Dow, 1986, 1993). This provided a potential neural substrate for the cerebellum partaking in cognitive (linguistic) besides motor related functions. With the introduction of state of the art non-invasive techniques, studies have recognized that the cerebellum plays a part in a wider spectrum of functions compared to what was preciously accepted, involving language (verb generation, e.g. Frings et al., 2006), memory (verbal working memory, e.g. Marvel & Desmond, 2012), executive functions (eye blink conditioning, e.g. Cheng et al., 2013) in addition to regulation and coordination of motor function.

Evidence in favour of a cerebellar deficit in dyslexia came from a wider cohort of neuroanatomical studies. Nicolson, Fawcett, & Dean (1995) reported time estimation impairments, unlike loudness estimation, when tested between a group of CwDys and Parkinson's patients. Although, such time estimation functions were not indicative of a direct cerebellar deficit, a follow-up study (Fawcett, Nicolson, & Dean, 1996) lent a strong direct support towards cerebellar deficits assessed using fourteen different clinical cerebellar tests. The findings from this study showed that CwDys, compared to both age and reading matched control group, were severely affected in all the tasks with the exception of a finger-to-finger pointing test (**figure 4**). In addition, findings consistent with poor acquisition of new and pre-learnt (automatic) motor skills characterized by a cerebellar deficiency in dyslexia were observed in PET studies (De-Kleine & Verwey, 2009; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Nicolson et al., 1999). Moreover, Nicolson and colleagues demonstrated anatomical findings revealing cerebellar asymmetries (significant difference in the mean cell count within the medial posterior cerebellar cortex and the anterior lobe with dyslexic brains having a large quantity of bigger cells along with a fewer number of smaller cells, Finch, Nicolson, & Fawcett, 2002), whilst a deficient cerebellar functioning also accounted for poor eyeblink conditioning (Coffin, Baroody, Schneider, & O'Neill, 2005; Nicolson et al., 2002). These findings were consistent with previous accounts of a persisting cerebellar abnormality, demonstrating potential motor learning deficits underlying dyslexia.

There has been mounting interest in the role of a dysfunctional cerebellum in other non-motor cognitive functions, especially with that of reading ability in dyslexia. Clinical findings from other patient populations (e.g. Richards et al., 2006) indicate that the posterior cerebellum controls language processing such as analysis of word forms (left cerebellar hemisphere) and phonological processing (right cerebellar hemisphere). In studies which investigated CwDys following cerebellar damage, reported deficits include specific difficulties in reading single (familiar words and nonwords), word sentences, along with a variety of oculomotor deficits (e.g. abnormal saccadic and pursuit eye movements; Bucci, Bremond-Gignac, & Kapoula, 2008a), poor binocular control (Bucci, Bremond-Gignac, & Kapoula, 2008b), unsteady fixation's (Moretti, Bava, Torre, Antonello, & Cazzato, 2002), and poor attention focusing (Rees, Frackowiak, & Frith, 1997) all of which served to disrupt the reading process. Additionally, Ben-Yehudah, & Fiez (2008) stated that the cerebellum may potentially be involved in supervising the timing of articulatory responses, second to a more general function in phonological error correction, further supported by recent studies (e.g. Golfinopoulos et al., 2011; Wolpert, Diedrichsen, & Flanagam, 2011). From these findings it is conclusive that cerebellar deficits do form what

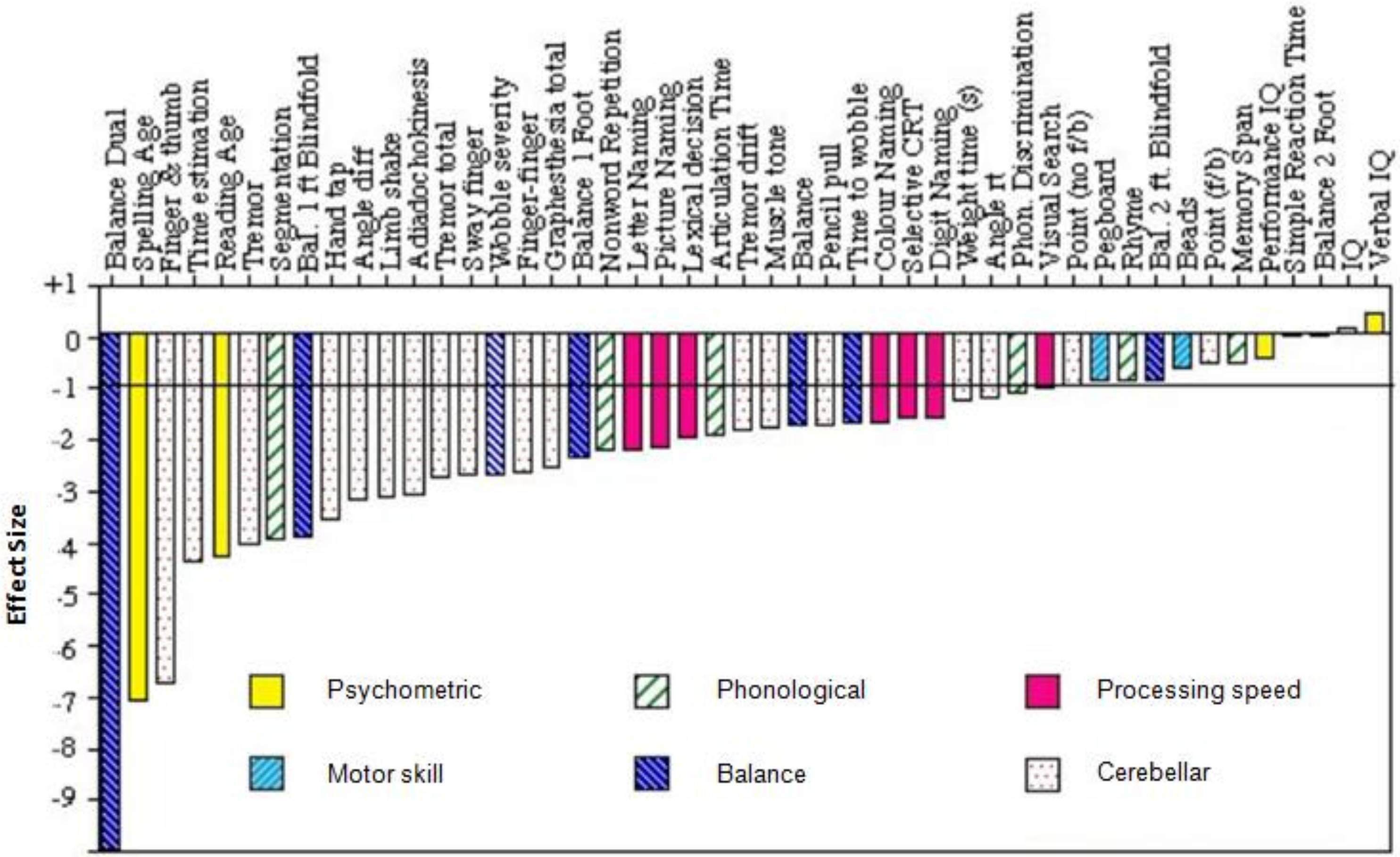

Figure 4: Large scale study of Fawcett, Nicholson and Dean (1996) demonstrating the various deficits associated in CwDys whilst performing cerebellar controlled tasks. [Source: Adapted from Pearson Education, Inc (2011)].

is an ideal anatomical substrate for automatisation and implicit learning, thereby having a significant influence on literacy development. Consequently, any shortcomings within the cerebellar architecture (e.g. verbal working memory, articulatory rehearsal system, etc) could hinder the process by which the letters gets recorded into a phonological code, the process considered to be an integral part of the articulatory control system. This could in effect result in articulation speed, one which is slower and that which takes up more conscious resources (leaving lesser resources for efficient processing of the resulting sensory response), such that a fewer amount of information eventually gets stored in the phonological loop present within the working memory (Baddeley et al., 1998). Moreover, clinical findings also provide evidence of cerebellar functions in the motor-linguistic domain (Ackermann, Mathiak, & Ivry, 2004) where poor motor coordination has an effect on handwriting skills of dyslexics, a skill requiring more conscious effort, precise timing and coordination of various muscle groups. Nicolson & Fawcett (1999) therein introduced the hypothetical ontogenetic causal chain of dyslexia highlighting difficulties with regards to the motor skill, working memory, phonological and literacy measures which manifests as a result of a cerebellar deficit (**figure 5**).

However, the CD theory has somewhat gained a mixed acceptance in the field of dyslexia. Similar to the findings made by Nicolson and colleagues (Fawcett & Nicolson, 1999, 2008; Fawcett, Nicolson, & Dean, 1996, 1998; Nicolson & Fawcett, 1990, 1994, 1995, 2000, 2005; Nicolson, Fawcett, & Dean, 1995, 2001; Nicolson et al., 1999, 2002), many studies using lesser complex paradigms have showed difficulties with regards to unstable postural control in both children and adult dyslexic populations in line with a cerebellar deficit (e.g. Barela et al., 2011; Brookes, Tinkler, Nicolson, & Fawcett, 2010; Bucci et al., 2013; Chaix et al., 2007; Legrand et al., 2012; Moe-Nilssen, Helbostad, Talcott, & Toennessen, 2003; Quercia, Demougeot, Dos-Santos, & Bonnetblanc, 2011; Stoodley, Fawcett, Nicolson, & Stein, 2005, 2006; Stoodley & Schmahmann, 2009, 2010). However, an obvious relationship between postural control and dyslexia remains inconclusive based from findings in other studies. First, studies employing a variety of balancing tasks between dyslexic and matched control samples have demonstrated impaired postural control in dyslexia (unlike in controls) only in some cases (e.g. Wimmer, Mayringer, & Landerl, 1998; Wimmer, Mayringer, & Raberger, 1999; Poblano et al., 2002; Ramus, 2003; Ramus et al., 2003; Raberger & Wimmer, 2003; Rochelle & Talcott, 2006), whilst certain studies have reported a complete lack of such group effects (e.g. Kapoula et al., 2011; Savage, 2007; Stoodley et al., 2006). For those studies showing partial support for cerebellar specific posture instability, some scholars have related such impairments to other co-morbid disorders such as ADHD (e.g. Kibby, Francher, Markanen, & Hynd, 2008;

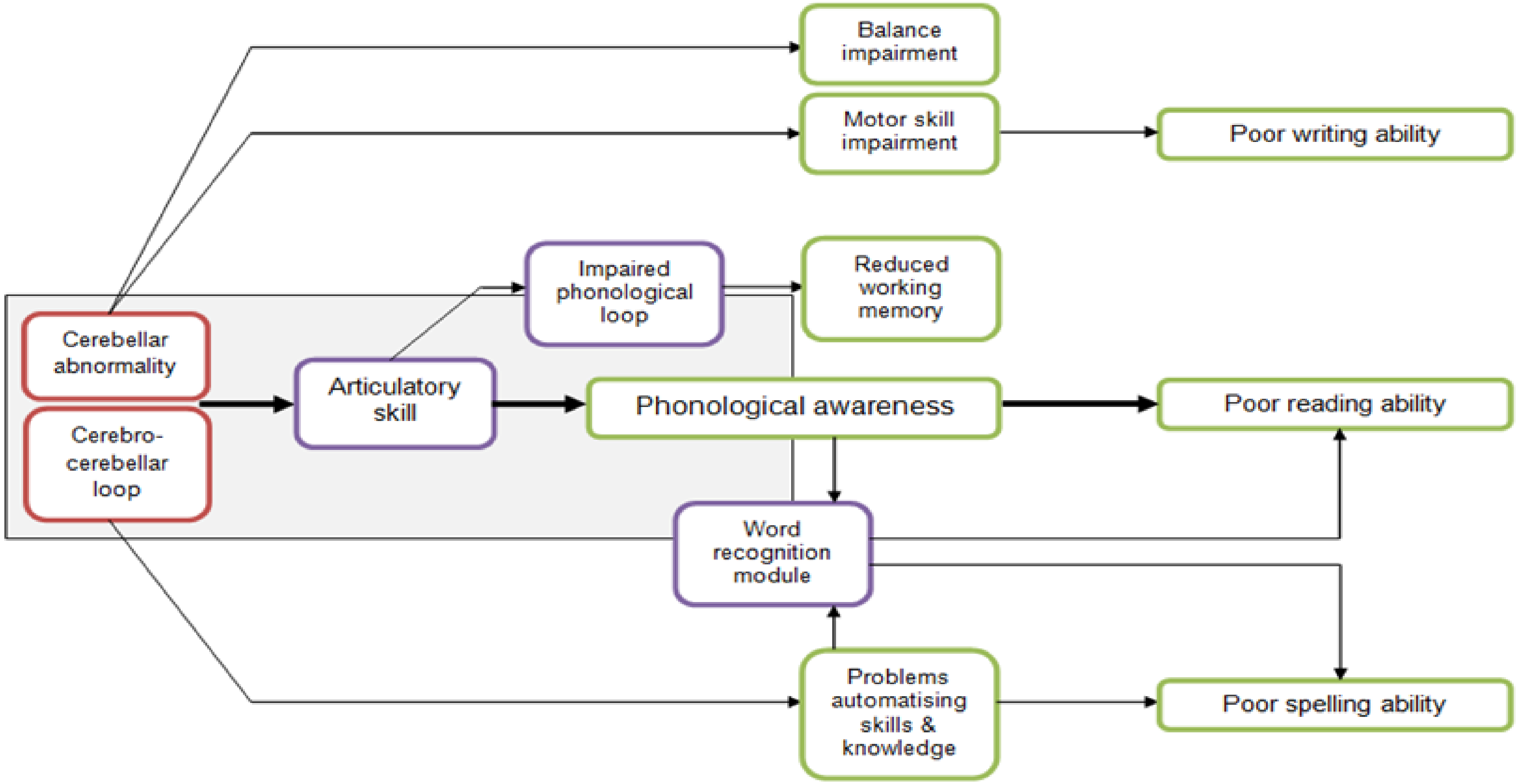

Figure 5: The hypothetical causal chain of the cerebellar deficit theory. The literacy difficulties in dyslexia are thought to arise from direct and indirect means from the onset of birth across various lifetime experiences leading up to difficulties in reading, writing and spelling among many others. The important progression is that highlighted within the grey box (central route). Any cerebellar deformity during birth results in problems related to motor and articulatory functions. Poor articulatory functions therein confer to weakened phonological representations (required for speech) which in turn have an effect on phonological awareness resulting in reading difficulties. The remainder of the routes summarizes problems that are likely to occur external to the phonological domain, indicative of a number of other co-dependent factors from which difficulties such as reading, spelling and writing might be derived from. [Source: Adapted from Nicolson, Fawcett & Dean (2001)].

Rochelle & Talcott, 2006; Wimmer et al., 1999), schizophrenia (e.g. Leonard et al., 2008) and autism (e.g. Penn, 2006). The effects of these joint abnormalities could have possibly lead to different symptoms, thus contributing to group differences in Nicolson & Fawcett's (1990, 1995) tasks (but see Brookes et al., 2010 for recent counter evidence). Second, for those studies not accounting for cerebellar specific posture instability, it could be a matter of cerebellar deficit not explaining all cases of dyslexia (Ramus et al., 2003; Stoodley et al., 2006). Third, the lack of consistent support between postural control and cerebellar specific deficit could also come down to discrepancies based on different methodological procedures used for diagnosis, for instance calibrated pushes (e.g. Fawcett & Nicolson, 1999; Ramus et al., 2003) in addition to active eye movements task while accessing postural stability (e.g. Kapoula & Bucci, 2007; Poblano et al., 2002; Stoodley, Talcott, Carter, & Witton, 2000). This could possibly be due to a sluggish and/or untimely functional integration of visual-motor responses which brought about a poor performance rather than it being a pure cerebellar deficit. Fourth, despite common methodologies between studies (e.g. Getchell, Pabreja, Neeld, & Carrio, 2007; Ramus et al., 2003; Stoodley et al., 2006), the findings of a motor difficulty particularly in the younger dyslexic children point towards a possible developmental delay affecting the level of maturation in functional systems solely concerned balancing, rather than it being an abnormality which prolonged into middle and later ages (further supported by Pozzo et al., 2006; Vieira, Quercia, Michel, Pozzo, & Bonnetblanc, 2009). Fifth, the inconsistent group differences could be also explained by factors such as IQ, task difficulty of one language/cognitive task relative to the balancing task, in addition to a possible recruitment bias (i.e. dyslexic participants from a clinic vs. those from schools) with regards to the dyslexic participants being tested (Ramus et al., 2003).

Of recent times, the idea of cerebellum and its precise role in reading has fuelled some level of controversy. Some authors believe that the cerebellum plays a precise role in motor learning. In fact several clinical, anatomical and functional imaging studies (Balsters & Ramnani, 2011) point towards a role for the cerebellum in higher order functions (for a review see Schmahmann, 2004). One of the key processes that govern successful attainment of reading fluency is the extent to which visually guided saccadic eye movements are smoothly coordinated. Considering a motor task of this nature, undoubtedly the cerebellum would play its part, and any dysfunctions associated with the cerebellar structure could therefore hinder reading fluency via incoherent visual representations consequently having an effect on reading speed as a result of the sluggish and imprecise eye movements. However, studies have shown that the cerebellum has a rich supply of visual magnocellular input (Stein, 2001). Therefore, any shortcoming based on the incoming contributions from the magnocellular system would in effect render the outputs from the cerebellum to be anomalous. However, studies show that cerebellum, via magnocellular functioning, does not appear to be a contender towards reading deficits in dyslexia. For instance, Talcott et al (2002) carried out a visual motion study to access the extent of visual magnocellular processing capabilities in children, with findings showing that magnocellular processing accounted for approximately 7% of the variance in literacy, hence a significant predictor of literacy skills. However, this was not the case with the study of Ramus et al (2003). Furthermore, Rae et al (1998) indentified a significant source of cerebellar input originating from the posterior parietal cortex in addition to abnormal proportions of metabolites both in the right cerebellum and the left parietal-temporal areas. Rae and colleagues argued that the imbalance in metabolites in both these regions was down to a magnocellular deficit (given the rich magnocellular projections to the cerebellum and parietal cortex). Therefore, one can expect both these regions to be influenced separately and to a varying extent given the diverse pool of dyslexic participants. In fact, Nicolson et al (1999) reported of differences in the activation patterns present (only in the eyes closed condition) pertaining to the right cerebellar hemisphere when comparing both the dyslexic and matched controls on a motor sequence task. Therefore, the chances of a deficient magnocellular system (within the visual domain) contributing to the overall motor task in dyslexia is very scarce. Furthermore, for studies which showed both magnocellular and cerebellar deficits occurring common to other populations not necessarily linked to dyslexia (e.g. normal children and those with autism with no reading difficulties; Ramus et al., 2004), in such cases it can be argued there is no apparent requirement for visual magnocellular and cerebellar deficits to induce any literacy difficulties. With the above criticisms taken together, even a link between a deficient cerebellum and dyslexia remain questionable.

1.5.5 Temporal Processing Deficit Theory

Temporal processing (TP) refers to the amount of information that can be processed in a given short space of time, important for the purposes of encoding stimuli that which is short-lived and rapidly varying. The TP deficit was proposed initially by Tallal, reasoning that dyslexia was a co-occurring result of an auditory deficit (Tallal, 1980; 1984; Tallal, Miller, & Fitch, 1993). Tallal and other proponents of the TP deficit believed that phonological problems arose as a result of a general auditory impairment (i.e. sound awareness). The seriousness of a TP deficit in dyslexia was initially brought to light when individuals, particularly children with specific language impairment (SLI), demonstrated poor awareness of sound when tested using auditory tasks referred to as modified temporal order judgement or repetition task. Contrasting differences in sound judgements were being made, with the CwDys showing poor performance in short sounds and fast transitions (75 msec), but not the long sound (400 msec) intervals, indicative of a processing deficit based on incoming auditory information that which is of a temporal nature, the term referred to as rapid auditory/temporal processing deficit. This was exactly the same finding which Tallal (1984) found in CwDys, which led her to presume that TP deficit was informally related to both these conditions. But these findings are not limited in scope, as studies have in fact shown support towards a TP deficit in CwDys with evidence of poor performance on a wide variety of other auditory tasks such as auditory gap detection (Chiappe et al, 2002b), frequency and amplitude-modulation detection (Goswami et al., 2002), frequency and amplitude-modulation discrimination (Amitay, Ahissar, & Nelken, 2002), auditory attention modulation (Facoetti et al., 2010), backward masking (Ramus et al., 2003), illusionary movement detection (Kronbichler, Hutzler, & Wimmer, 2002), and phoneme perception (Serniclaes, Sprenger-Charolles, Carre, & Dermonet, 2001).

According to Tallal, Miller, & Fitch (1993) and Tallal et al (1996), crucial is the processing of short sounds and fast transitions for the development of accurate perception of contrasts needed for efficient speech production. Speech consists of variant acoustic cues that aid in distinguishing speech sounds which are usually of separate phonetic grouping. For instance, when it comes to syllables containing stop consonants, i.e. "/bA/" and "/dA/", the auditory cue decisive for accurate differentiation of these two sounds depend entirely in the initial period (roughly 100 msec), where the frequency components (formants) to follow thereafter changes in quick succession (a form of temporal cue). Tallal, in one of her earliest studies showed that CwDys found it difficult to distinguish between speech sounds within the first 40 msec of frequency transition, indicative of a deficit in processing brief rapidly presented auditory temporal cues (Tallal, 1980). The same was true based on the findings from other studies showing poor performance of dyslexic individuals when perceiving phonetic contrasts such as stop consonants (e.g. Bogliotti et al., 2008; Gerrits & De-Bree, 2009), with impairments observed even in the perception of speech rhythms (e.g. Goswami et al., 2011). Witton et al (1998), in an attempt to investigate possible temporal auditory deficits in dyslexia, showed that AwDys (in comparison to controls) revealed less sensitivity towards 2 and 40 Hz frequency modulation, but not 240 Hz. In the context of 2 and 40 Hz, tone detection was attained via a "temporal process", whereby changes in the time variant frequency of the sound source were constantly tracked. In the case of 240 Hz, a "spectral process" ensured that a spectral frequency separate to that carried by the frequency of the sound source was constantly tracked. For accurate speech perception, the amplitude and frequency changes modulated by both these process require being constant but accurate tracked. Therefore, any impairment in amplitude and/or frequency modulation detection could therein affect normal development of phonological skills via speech perception. Based on this sensitivity measure of both the 2 and 40 Hz frequency modulation, Witton et al (2002) further demonstrated a strong correlation between such measures to phonological decoding skills in both adult control and dyslexic individuals. Furthermore, Vandermosten et al (2010) demonstrated auditory deficits in AwDys in both speech and non-speech differentiation tasks, indicating that the TP deficit is not entirely speech-specific. In addition, they reported a strong correlation linking the performance at both temporal conditions to reading and spelling measures. This goes to show that a minor deficit, especially in the timing of such formants, could therefore significantly hamper the formation and bridging of robust internal speech-sound representations resulting in weaker phonological development (e.g. Bogliotti et al., 2008; Noordenbos, Segers, Semiclaes, Mitterer, & Verhoeven, 2012; Snowling, 2000) which may then go on to negatively influence the tuning capacity of the auditory system rendering poor perceived speech sound differences, i.e. "acoustically noisy" (Hornickel & Kraus, 2013; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009).

Like all other theories, even the TP deficit theory had received a fair share of criticism given the inconsistency of an auditory specific deficit within the dyslexic population (Ramus, 2003). First, criticisms was based on the ambiguity of findings initially demonstrated by Tallal (1980), where he claimed that impaired perception of short sound intervals and transitions would be particularly unfavourable to speech perception, thereby weakening the development of phonological representations. However, the opponents of Tallal argued that a low incidence of dyslexia existed for processing deficits observed at short sound intervals (e.g. 2 Hz, White et al., 2006) balanced with normal performance at long sound intervals (e.g. 240 Hz, Rosen, 2003), the latter due to both the control and dyslexic groups attaining optimum performances. Same was true with the detection tasks which (i) manipulated temporal sound intervals (Share, Jorm, MacLean, & Matthews, 2002), (ii) modulated frequency and amplitude tested at elevated temporal frequencies (Goswami et al., 2002), (iii) varied levels of task difficulty (Banai & Ahissar, 2004), and (iv) calibrated fast changing noise stimuli (Montgomery et al., 2005). Such findings was criticised on the basis that auditory deficit was regarded as a collection of an extensive range of complex spectra-temporal properties (Ramus et al., 2003). Second, the type of studies conducted to study these TP deficits in dyslexic population appeared under the spotlight. For instance, some studies was being criticised for focusing on a targeted skill to which dyslexics were known to suffer the most, e.g. auditory processing, speech and/or phonological processing, rather than considering the proposed battery of pathways at every possible level of analysis (White et al., 2006). Third, although studies claimed to have found difficulties in detecting a brief yet rapid stimulus (e.g. "/bA/" and "/dA/", Ahissar et al., 2000, 2001) with restrictions in attaining full TP ability linked to insufficient rate of information transfer to more complex processing (e.g. speech segmentation), however, this could have been actually down to a difficulty in stimulus identification as it seems to sit well with other temporal coding difficulties which dyslexics are known for, especially in prosodic perception of speech (Goswami, 2011; Goswami, Gerson, & Astruc, 2010; Mundy & Carroll, 2012). In fact, several studies had successfully replicated such findings consistent with other tasks requiring identification in prosodic perception using both stress perception (Leong, Hamalainen, Soltesz, & Goswami, 2011) and music perception (Huss, Verney, Fosker, Mead, & Goswami, 2011) tasks. The weakness in ability to perceive auditory musical beats in dyslexic individuals were consistent with the difficulties previously observed in syllabic stress perception. Moreover, difficulties consistent with stimulus capture, known to be functionally operational around the same temporal spectrum, were established in both Ahissar et al (2001) and Yehudah et al (2004). Taken together, the reason why poor processing within this temporal range gives rise to weak amplitude frequency discrimination could then be related to the lower frequency range in which some of the above deficits were observed, which probably reallocates to the focal point of the contrast between the perceptual and attentional mediums. Evidently, frequencies as low as 2 Hz may therefore set apart attentional processes required for perceptual integration and explicit object identification.

Importantly, studies using data pooled across groups for reporting auditory deficits was being further criticised, given that any associated problems would for the most part be evenly distributed among reading impaired individuals. Also, it was of general concern to some scholars (e.g. Ramus et al., 2003) that certain crucial findings may have a tendency to go unnoticed when considering correlational data across participant groups. Ramus and colleagues examined a group of AwDys with reports detailing auditory deficits to be limited to just 39% of participants within their dyslexic group, and it was this minority of dyslexic participants which demonstrated a weaker correlation between auditory temporal processing with that of phonology and reading. In the case of low-level sensory problems, deficits were usually observed in a minority of dyslexic individuals present within a study sample, the reason why some studies have reported correlational data carried out separately for each participant group, thereby further questioning the validity of findings of an auditory temporal deficit as a main contributor towards reading difficulties in dyslexia (e.g. Ramus, 2003; White et al., 2006). Furthermore, it is also of paramount importance that any findings related to dyslexia are not just measured but the performance has also got to be delineated as abnormal in a clear cut fashion, achieved via demonstration of a higher percentage of individuals having performances that significantly varies from the control (e.g. Pech-Georgel, George, & Lorenzi, 2008; Ramus et al., 2003). That is, even within-group comparisons could possibly disguise significant individual differences (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009). Hence, it is crucial for studies, especially in dyslexia, to demonstrate both significant group and individual differences. Given such statistical and methodological shortcomings in previous research, inconsistent findings related to temporal processing only yields further ambiguity making it even harder to separate the poor from good performances of individual dyslexics.

In addition to TP difficulties in the auditory domain, certain studies have also demonstrated evidence for constraints in visual temporal processing especially when coping with brief and rapidly occurring visual stimuli (e.g. Boets et al., 2007; Habib, 2000; Walker, Hall, Klein, & Phillips, 2006). Initially, studies carried out using both individuals with dyslexia and control readers came up with some interesting findings, one of which was the need for more inter-stimulus separation apart two word stimuli in order for dyslexic readers to identify them as separate (Stanley & Hall, 1973; May, Dunlap, & Lovegrove, 1988). The authors claimed the longer stimulus onset asynchrony (SOA) taken to process the visual stimulus to be a result of poor TP in individuals with dyslexia. This paved way for more complex studies attempting to investigate both temporal and spatial processing of visual stimuli in the dyslexic population (e.g. Boets et al., 2007; Eden et al., 1995; Ingelghem et al., 2001), with some studies showing significant correlations between poor visual processing ability with that of orthographic (Boets et al., 2008) and word reading (Au & Lovegrove, 2008) ability. However, this was not the case with all studies, as some have in fact shown no support towards a modality specific impairment of TP deficits (Dawes, et al., 2009), whereas other studies have reported a fewer number of dyslexics within the study sample demonstrating visual temporal processing deficits (Gibson, Hogben, & Fletcher, 2006; Wright & Conlon, 2009), with such measures showing poor correlation towards orthographic skill (Chung et al., 2008; Landerl & Willburger, 2010). Exactly how this link manifests within dyslexic populations still remains somewhat vague. Nevertheless, in the last two decades alone, sensitivity both in the auditory and visual modality has been increasingly considered in the framework of magnocellular processing (see Nicolson & Fawcett, 2008 for a review). One might therefore expect to find temporal auditory as well as visual difficulties to be interrelated with the processing deficits of magnocellular functions (similar to that proposed by Boets et al., 2007;

Ingelghem et al., 2001). Such temporal processing difficulties could be further linked to an attentional difficulty given that the activation of parietal brain regions is directly related with controlling of attention, thus negatively influencing rapid processing skills (Corbetta & Shulman, 2002). This is applicable in a situation when directing attention towards every successive stimulus (auditory or visual), or when sustaining attention for a required period of time for each incoming stimulus, both which are of sole importance for accurate processing and stimulus identification.

1.5.6 Visual and Magnocellular deficit theory

In terms of vision in a clinical setting, individuals with dyslexia are not known for possessing any particular visual deficits just like in typical readers. As previously mentioned, reading deficits in dyslexia are much more connected to non-visual aspects of reading (i.e. the ability in being able to decode visual symbols into corresponding phonemes), so much so that it significantly hampers reading at a more syllabic level as characterized by poor ability in naming speed (Denckla & Rudel, 1976), and word rhyming (Bradley & Bryant, 1978). But one needs to ponder as to why some dyslexic individuals do not fully achieve their quota of phonological skills despite recompensing to some degree (e.g. with the help of learning remediation). Essentially, one needs to be able to visually analyse words in order to precisely partition them for efficient characterization of phonemes. But for this to take place, one need to be aware as to how particular phonemic components are visually represented by letters in a printed form, so visual analysis of words is a perquisite. This eventually depicts the level of phonological awareness skills achieved by a reader. Therefore, the visual theory of dyslexia does not entirely eliminate phonological deficits, but it lays emphasis on a significant visual contribution in reading problems (**figure 6**).

Reading is a complex process in its own right, but when it comes to visual contributions it poses further demands on processing efficiency. For instance, visual processes in reading includes, first, scanning a page of text which requires a stable focus along with rapid and accurate sequential eye movements in one specific direction (**figure 7**). It is during this period where different textual properties (e.g. shape, size, colour, spacing, orientation, etc) are identified. Any difficulty in stably locating letters/words would result in the reader losing the position on a line of text (as both the eyes end up pointing out of phase with each other), with letters/words becoming blurry and scrambled across locations, further resulting in misidentification and missequensing of letter/word(s). Such disordered vergence control of letter/word(s) would cause the reader to have an inadequate sense of

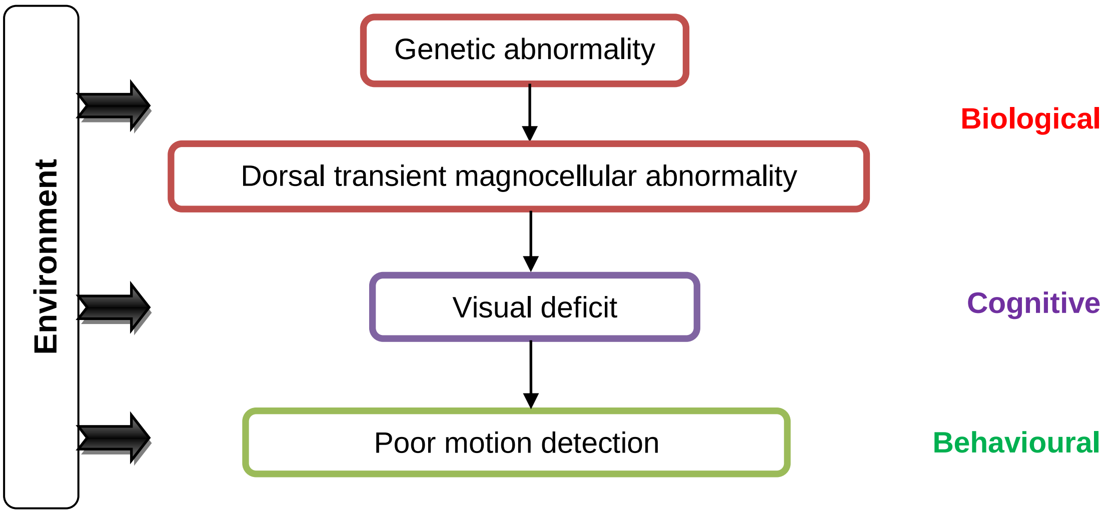

Figure 6: Proposed cause of dyslexia according to the magnocellular deficit theory. [Source: Adapted from Frith (1997)].

visual direction. In the worst case scenario, this could further result in a build up of visual stress/strain, a condition that incites distortions (e.g. "b" appearing as "p" and/or "q") in visual perception resulting in impaired reading fluency (Singleton & Trotter, 2005). Second, the reader must be able to move their eyes quickly (i.e. saccades) from one salient position to another (usually at the neighbouring word/s) following a very brief fixation period (usually in the order of 100 – 300 msec), so as to bring all the salient visual fields into focus. Both the saccades and fixations are coordinated by a highly complex visual system, the former being processed to describe "what" was being looked by the reader, whilst the latter describes "where" the reader needs to look next. Any fault with regards to the saccadic sequence, unstable binocular fixations and/or poor coordination between the two processing centres can therefore result in the reader experiencing laborious jerky eye movements. Third, visual attention acts as an external contributor towards the control of saccades such that attention is allocated to the chosen letter/word target shortly before execution of the saccade. In this way, visual attention ensures that a stable line of sight is maintained over a small, salient, yet fully attended target letter/word whilst ignoring the large, non-salient distractors in the surrounding periphery. The capacity in accurately guiding ones attention focus item by item at a time also serves to overcome visual saturation effects, particularly crowding of potential salient targets. With each fixation that sweeps across the line of text, the words are processed in a temporal fashion. Therefore, a subtle deficit in any one or combination of these functions affects the reading process by hindering the intake of crucial visual information necessary for the development of spelling-to-sound correspondences, thereby suggesting that visual deficits do play a part contributing to phonological errors. In an attempt to investigate potential visual deficits in the aetiology of dyslexia, studies in the 90's discovered problems related to disordered vergence control (Eden, Stein, Wood, & Wood, 1994; Stein & Fowler, 1993), visual stress (Wilkins, 1995), unstable binocular fixations (Stein, 2001), visuospatial attention deficits (Hari, Renvall, & Tanskanen, 2001), and increased visual crowding (Spinelli, Luca, Judica, & Zoccolotti, 2002).

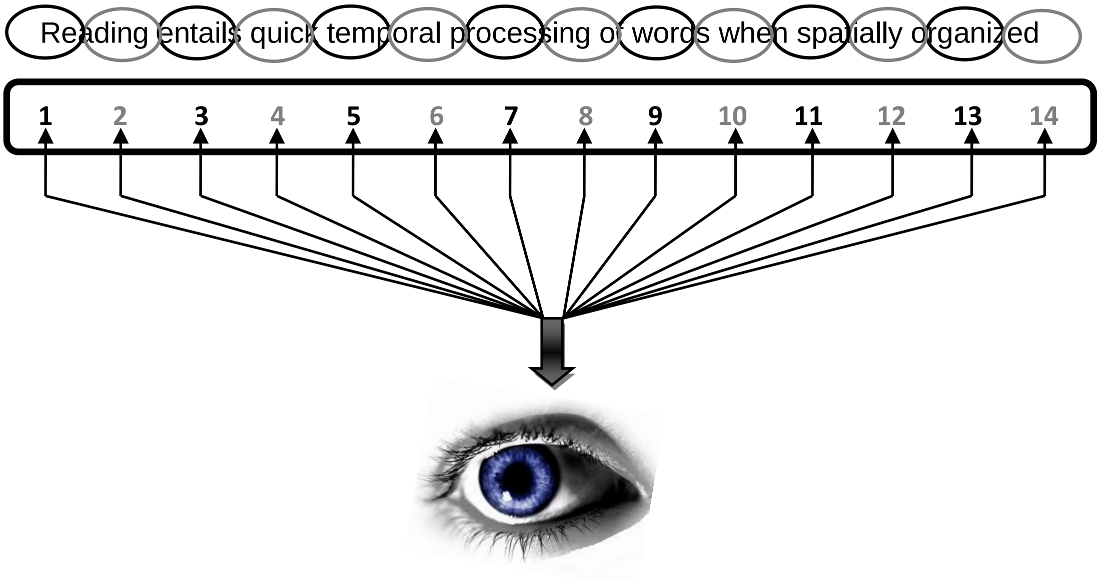

Figure 7: Spatial and temporal order visual acquisition during a reading task. To read a line of text which spans from left to right (e.g. in English), one performs repetitive fixations further aided by relocating spatial attention, in a way such that the incoming information can be processed rapidly and accurately. Any short-comings in the ability to make accurate fixations and/or guide ones spatial attention could result in inaccurate processing of visual stimuli. [Source: Adapted from Laycock & Crewther (2008)].

At the biological level, the visual dysfunction in dyslexia is understood as a deficit affecting visual system, one which connects the retina present within the eyes via the hierarchical processing pathways allowing information to be processed by the specific areas of the brain. The visual system consists of two distinct but parallel visual pathways, namely parvocellular (sustained system) and magnocellular (transient system), both located within the lateral geniculate nucleus (LGN). Both these visual pathways vary based on certain physiological properties, namely sensitivity towards contrast, colour, along with temporal resolution and sharpness (acuity). Depending on the type of visual information arriving at the striate cortex via these two pathways, it is then further conducted via two up-streams, dorsal and the ventral stream, which then gets further projected on to separate layers of the primary visual area (V1) within the occipital cortex, i.e. parietal and temporal cortices (Livingstone & Hubel, 1988). Crucial to the function of the dorsal processing stream are two regions, namely the middle-temporal area (MT area/V5) linked with motion perception, and the posterior-parietal cortex (PPC) linked with processing spatial attention (Vidyasagar & Pammer, 1999, 2010). In the case of the latter, the incoming dorsal projections help PPC to produce a spatial map which then projects back to the ventral areas forwarding information regarding the lexical properties (e.g. line orientation between "W" and "M") which is then transmitted via the parvocellular pathway offering detailed positional information during the encoding process required for efficient reading (Goodale & Milner, 1992).

While the pathways governing the transfer of information to be processed efficiently are complex, so are the functional attributes of these individual pathways. On one hand, the smaller neurones (having smaller receptive fields) present within the parvocellular (ventral) pathway responds slowly to medium and high spatial along with low temporal frequencies of incoming information, thereby demonstrating greater sensitivity towards colour and fine spatial details (Shapley, 1990). This pathway is therefore crucial when verifying "what" was being looked at. On the other hand, the larger neurones (having larger receptive fields) present within the magnocellular (dorsal) pathway possess high transmission speeds demonstrating greater sensitivity towards low spatial and high temporal frequencies incoming information, such as abrupt changes in movement within a given visual field (Merigan & Maunsell, 1993). This pathway is therefore crucial when verifying "where" an object is precisely located in space. When it comes to reading, the parvocellular pathway is thought to be effective during binocular eye fixations, whilst the magnocellular pathway comes into use during the initiation of saccadic eye movements. The magnocellular pathway is assumed to play an important role in suppressing the parvocellular pathway when the eyes are subjected to constant movement. This inhibitory process acts so as to prevent the accumulation of a "stimulus after-trace" present from the previous fixation which normally extends for a brief period (approximately 220 – 250 msec’s) following stimulus offset, the term normally coined as visible/trace persistence. Therefore, the time-span of this visible persistence is pretty much decided upon the speed of processing via the transient magnocellular pathway necessary for steady fixations, besides guiding eye movements at fixation intervals.

The earliest of studies became highly focused on deficits related to visual motion in poor readers as they firmly believed that the reduced sensitivity of the visual system gave rise to weaker reading ability (e.g. Lovegrove et al., 1986; Wright & Conlon, 2009). The advantage of having two separate pathways offered the flexibility for scholars to assess their sensitivity levels towards stimuli intended to activate either one of both pathways using psychophysical tests. Lovegrove and colleagues designed a set of experiments to examine the variations in sensitivity of the visual system towards visible persistence between a group of control readers and individuals with dyslexia. In Martin & Lovegrove's (1984) study, visible persistence was measured by subjecting both groups of participants to alternating sinusoidal wave of sequences with narrow black and white gratings, thereby requiring the participants to indicate the presence or absence of a blank space between gratings. The time required to distinguish the two visual stimuli presented in rapid succession provided a measure of magnocellular pathway sensitivity. The findings from the dyslexic group showed a failure in detecting a blank space, indicative of a prolonged visible persistence. Findings have in fact demonstrated visible persistence in dyslexics to last longer by a further 100 msec especially towards contrasts at low spatial frequencies (e.g. Slaghuis, Lovegrove, & Davidson, 1993), whilst truncated visible persistence showed greater sensitivity towards contrasts at higher spatial frequencies (e.g. Talcott et al., 1998). In reading, any "masking" due to prolonged visible persistence could therefore result in the letters (within a word) being superimposed one on top of each other and jumbled up causing confusions in the mind of the reader (Eden et al., 1994). That is, should the amount of inhibition exerted by the magnocellular on the parvocellular pathway becomes any less, it results in the activity generated by parvocellular pathway during one fixation to be confused with that generated from the next. Based on these findings, it was suggested that a specific impairment in the transient magnocellular system concerned with processing rapid changes in the visual modality resulted in poor acquisition of orthographical skills experienced by dyslexic individuals (e.g. Stein & Talcott, 1999; Vidyasagar, 2004; Wright & Conlon, 2009).

Further evidence of such an impaired transient magnocellular system in dyslexia was reported from a variety of other studies assessing visual perception and contrast sensitivity (e.g. Stein, 2001). For example, using behavioural psychophysical techniques, studies have shown that the contrast sensitivity pattern significantly varied between CwDys and control children, in that, the CwDys were less sensitive for rapid visual changes at low spatial frequencies (1, 2, and 4 cycles deg^{-1}) compared to higher spatial frequencies (8 and 12 cycles deg^{-1}) where their sensitivity was great (Cornelissen et al., 1995; Habib, 2000; Livingstone, Rosen, Drislane, & Galaburda, 1991; Talcott et al., 1998, 2000). Since efficient reading demands a rapid and precise processing of transient stimuli, some scholars were able to demonstrate a strong correlation between motion processing deficits to phonological decoding accuracy in both the child and adult dyslexic populations (Talcott et al., 1998, 2002). Findings with regards to a deficient transient pathway were also reported given the poor performance of CwDys at spotting coherent motion when examined using random dot kinematograms (Pammer & Wheatley, 2001). The same was true when it came to dyslexic children at perceiving global motion at shorter inter stimulus intervals (ISI) using specialized illusion tasks. For instance, the use of frequency doubling illusion measured the modulation of the magnocellular-cell activity, to tasks such as coherent motion and visual acuity. Despite a relatively good performance in the visual acuity task by the dyslexic group, it was demonstrated that these very individuals performed far more poorly in the frequency doubling and coherent motion illusion compared to the control group, suggesting a potential magnocellular deficit initiating at the retinal level (Buchholz & McKone, 2004; Pammer & Wheatley, 2001). Other scholars demonstrated significant correlations between coherent motion thresholds and letter decoding skills (Talcott et al., 2002), in addition to that between motion speed discrimination and reading speed (Wilmer, Richardson, Chen, & Stein, 2004) in a sample of CwDys. The motion sensitivity measured in this way better explained any discrepancies in the index of visual/orthographic reading skill separate of any links with phonological ability.

Evidence in favour of a magnocellular dysfunction in dyslexia comes from anatomical studies conducted by Galaburda and colleagues. The initial set of post-mortem studies (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985) investigated five brain specimens, reporting evidence of abnormally developed neurons (ectopias) and distorted cortical regions (dysplasia), most of which were found in the perisylvian cortex lateralized on the left hemisphere for the males (similar findings in Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006). Galaburda et al (1985) suggested that such variations in structural brain reduction reflected poor neuronal migration during foetal development. The researchers also noticed the presence of an asymmetry situated within the planum temporale, a region which occupies a portion of the Wernicke’s area concerned with speech comprehension, especially on the expanded right hemisphere planum. Galaburda, Corsiglia, Rosen, & Sherman (1987) suggested that such variations in asymmetry reflected diminished cell death on the right hemisphere during the later stages of foetal development which paved way for the survival of more neurons on one half resulting in an imbalanced brain architecture. The researchers also investigated for potential abnormalities of the magnocellular layers of the LGN, where they identified a disorganised neuronal distribution when comparing the brain specimens of dyslexics to the controls (Livingstone et al., 1991). They reported the sighting of a larger quantity (70%) of smaller neurones along with a fewer number (30%) of larger neurones within the left-LGN of dyslexics. Furthermore, the LGN neurones present within the left hemisphere were significantly smaller than those in the right hemisphere of the dyslexic sample, compared to a lack of such asymmetry in the control sample (Galaburda, Schrott, Sherman, Rosen, & Denenberg, 1996). For the sake of argument, the researchers were also keen in knowing whether this was the same pattern of distribution with the medal geniculate nucleus (MGN) of the auditory modality. Moreover, Galaburda, Menard, & Rosen (1994) also found far more significantly smaller medal geniculate nuclei's (MGN) on the left, compared to the right, hemisphere in dyslexic specimens, attributing MGN differences to a slowness of information processing within the parvocellular channels resulting in temporal processing difficulties (i.e. auditory confusion of letter sounds impairing the acquisition of phonological skills). In another observation made by Jenner, Rosen, & Galaburda (1999), despite the uncharacteristic grouping of the cortical neurons, these neurones in dyslexic brain specimens did not have the same pattern of magnocellular inputs from the thalamus, thought to be due to a poor grouping of both magnocellular and parvocellular pathways. On the whole, with regards to the structural variations in the LGN, any reduction of magnocellular cell size could have detrimental effects in individuals with dyslexia, such that a reduced number of magno-cells results in an underestimated sample of moving stimuli, the reason why poor readers find themselves less sensitive to stimulus movements.

Findings from both functional magnetic resonance imaging (fMRI) and electrophysiological studies have also lent some support towards a deficient magnocellular system in dyslexia. Eden et al (1996) investigated the change in the activation levels (as depicted by the local blood oxygenation level dependant, BOLD signals) between a group of control adults and AwDys in a task which required passive viewing of moving dot stimulus patterns (tapping magnocellular pathway) and a stationary stimulus pattern (tapping parvocellular pathway). For the former, a clear activation of the MT area was observed in the control group, whilst for the latter both groups showed similar activation in the posterior occipital cortex and extrastriate regions (fusiform and the inferior temporal gyrus) during the stationary pattern. Demb, Boynton, & Heeger (1997, 1998) looked at activation patterns between a group of control adults and AwDys pertaining to moving stimuli having various contrasts (tapping magnocellular pathway) versus a control stimuli (tapping both magnocellular and parvocellular pathways). Findings from these studies showed a degraded activity of the primary visual area (V1) and accompanying extrastriate areas (MT, and the medial superior temporal – MST areas) in response to the moving stimuli as witnessed in the dyslexic group. It must be noted that both the MT and MST areas serves important connections, where MT receptive fields mainly serves to encode the contralateral visual field, while MST receptive fields project to the ipsilateral visual field, in addition to smooth pursuit eye movement inputs. Furthermore, electrophysiological studies using visual evoked potentials (VEP) testing uniform/random motion paradigm in CwDys demonstrated longer latencies together with smaller amplitudes evoked by rapidly changing/moving stimuli consistent with evidence of a magnocellular deficit at the level of V1 and/or earlier (Livingston et al., 1991). It is worth mentioning that the electrophysiological studies of this kind assessing visual motion processing to a rapidly moving stimulus have shown a trigger pertaining to both a P1 and N2 components[2]. Between motion-type comparisons in AwDys revealed an N2 component which was similar in response to both the uniform and random motion with no significant differences between motion types. The N2 amplitude of the dyslexic group was significantly more negative for random motion than the control group. The N2 amplitude pertaining to random motion significantly correlated with spelling ability for both control and AwDys, consistent with previous psychophysical outcomes linking a deficient magnocellular pathway in orthography skills (e.g. Talcott et al., 2002; Sperling, Lu, Manis, & Seidenberg, 2003; Wilmer et al., 2004; Shachar, Dougherty, Deutsch, & Wandell, 2007).

However, not many scholars were fully convinced of a deficient magnocellular system giving rise to phonological problems in dyslexia. The first of many criticisms fuelled against the magnocellular system was based upon the earliest findings of Hulme (1988) who observed significant reading errors in CwDys, compared to controls, when asked to read out single words and nonwords presented sequentially. According to the magnocellular deficit theory, one would expect a significant reading impairment by the dyslexic individuals especially when reading connected text and not when reading sequentially presented printed words in conditions that are most suitable for foveal vision. Additionally, Lovegrove and colleagues in their studies reported a significant number of normally reading control participants in line with a transient magnocellular pathway deficit, despite some of the dyslexic individuals showing no clinical signs of visual perceptual anomalies (e.g. visual acuity and masking) under normal viewing conditions. Also, the phonological deficits observed in these CwDys have been correlated with reading difficulties (phonological awareness and orthographic skills). Eden, Stein, Wood, & Wood (1995) made a valid point by indicating that the visual processes contributing to such unique variances in predicting reading skills could have actually been far smaller compared to the variance offered by independent phonological measures. Given this

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[2] P1 refers to a brief positive overshoot of the VEP wave occurring at approximately between the 95th and 110th msec, with its neuronal input likely to be generated from the extrastriate cortex of the middle occipital gyrus. N2 refers to a brief negative undershoot of the VEP wave occurring at approximately between the 50th and 200th msec, with its neuronal input likely to be generated from the MT+ cortical area (Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2002).

exaggerated phonological measures portrayed by the findings of Lovegrove and colleagues, Hulme argued that such reading difficulties was not due to the visual masking effect (generated by a transient magnocellular system deficit), instead he supports the view of Vellutino et al (2004) stating that the masking effect due to prolonged visual persistence was an associate or biological marker, rather than a cause, of reading difficulties.

Studies investigating links between magnocellular deficits and reading difficulties in dyslexia have also reported of an absence of reading disorder, and in most cases a significant overlap in performance between skilled and dyslexic readers, hence further questioning the validity of this theory (e.g. Heim, Grande, Pape-Neumann, Ermigen et al., 2010; Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Skoyles, & Skottun, 2004; Vellutino et al., 2004). Interestingly, findings from some studies report of reading deficits not associated with magnocellular deficits all together. For instance, despite the evidence of a magnocellular deficit demonstrated by CwDys, Sperling et al (2003) reported that such measures correlated negatively with reading impairments, i.e. certain participants with greater reading deficits was reported to perform normally in the visual magnocellular tasks. If any, this goes to show that magnocellular deficits may possibly be a derivative of dyslexia, budding alongside deficits which are more of a primary cause towards the reading problem (Ramus, 2004). By tagging the aforementioned findings together, these could possibly reflect deficits of impoverished magnocellular function solely due to poor reading experience rather than a core magnocellular deficit. This is the case since certain studies have demonstrated evidence of improved visual motion perception with age as observed in typically reading children. Such participants eventually demonstrate weaker reading performances in comparison to their adult counterparts (e.g. Boets et al., 2011), suggesting that reading fluency gained by learning interventions is only going to trigger the visual magnocellular system even further (e.g. Olulade, Flowers, Napoliello, & Eden, 2013). This further goes in line with the reported behavioral deficits based on a variety of other visual magnocellular tasks, whereby such deficits were concluded to be a consequence of reading disability rather than a causal factor of dyslexia (e.g. Hansen et al., 2001; Meng et al., 2011; Talcott et al., 2003; Witton et al., 1998). Thus, in a way Stein, Talcott & Walsh (2000) could be right with the claim that they made in that "…many, if not most, developmental dyslexics have mildly impaired development of the visual magnocellular system has taken firm root…", which just about questions whether the observed magnocellular deficits is either correlational or causal with regards to its relationship with reading difficulties in dyslexia.

The outcome of a number of independent research groups has also offered various other evidences contrary to the basis of the magnocellular deficit theory of dyslexia. There is evidence of the magnocellular pathway being suppressed by, rather than being a suppressor of, the parvocellular pathway during saccades (e.g. Hogben, 1997; Skottun, 1997; Skottun & Parke, 1998). In an attempt to determine both spatial and temporal contrast sensitivity functions (using a 2 cycle deg^{-1} grating, i.e. the critical spatial frequency where detection is thought to swing from magnocellular to the parvocellular pathway), the dyslexic group showed both a reduced spatial and temporal sensitivity (Martin and Lovegrove, 1987). The authors discussed their findings within the context of a transient magnocellular deficit. Nonetheless, a notable widening of this reduced sensitivity function (from 5 to 25 Hz) was evident on gradual increase in spatial frequency. In normal circumstances, it is expected that the VEP amplitude for a particular stimulus contrast increasing linearly eventually saturates at higher contrasts corresponding to the magnocellular pathway (Zemon & Gordon, 2006). The finding by Martin & Lovegrove (1987) therefore goes against the original magnocellular deficit theory, as for the latter, the loss in contrast sensitivity was predicted to be at its peak at lower spatial frequencies. Another study investigated the temporal contrast (flicker) sensitivity for rapidly changing stimuli surrounded by an area of matching luminance (Brannan & Williams, 1998). CwDys, unlike controls, demonstrated reduced contrast sensitivity amongst the entire batch of frequencies tested (4, 8, 12, 16, 20, and 24 Hz). In particular, the reduced sensitivity in modulation happened to take place at low and medium temporal frequencies (i.e. 4, 8 and 12 Hz) which again questions the viability of the magnocellular theory. Considering both these studies as a whole, in fact it could have been a result of a parvocellular rather than a magnocellular deficit. That is, the motion inducing stimulus could have introduced a precise boundary between the contrast of the flicker and the surrounding luminance during individual segments of the flickering sequence. In essence, this boundary contained within an array of frequency component could have actually supplied a stronger, yet effective stimulus input, for the parvocellular system. Therefore the problem could come down to studies not being able to test both the magnocellular and parvocellular pathway separately.

Nonetheless, some electrophysiological studies have utilized stimuli which targeted the response of either one of both magnocellular and parvocellular pathways producing results which tapped on to a wide range of mechanisms pertaining to various spatial frequencies, not limited to the magnocellular pathway alone (e.g. Brecelj, Strucl, & Raic, 1996; Livingston et al., 1991). One study in particular carried out by Ellemberg et al (2001) investigated the magnocellular deficit in control adults isolating the characteristic responses from both the magnocellular and parvocellular pathways. The researchers used vertical sinusoidal gratings to measure the VEPs to rapidly changing contrasts. In doing so they observed a lower spatial frequency (less than 2 cycles deg^{-1}) characteristic of the P1 component wave (signalling pure magnocellular contrast response), whilst a higher spatial frequency (less than 2 cycles deg^{-1}) characteristic to the N1 component wave (signalling a pure parvocellular contrast response), the difference of the two pathways achieved by a alternating intermediate stimuli with medium contrast. A recent study replicating this within a population of CwDys and matched controls showed no significant variations in the amplitude of VEP components related to either of the pathways (Sayeur et al., 2013). The only group difference which immerged was the variations in the distribution of amplitudes, which happened to be underactivated in the frontal and left temporal regions (involved in phonological processing) for CwDys. Taken together, these findings are yet again inconsistent with the magnocellular deficit.

Further criticisms have been put forward in line with the discrepancies characteristic to differences in the participant populations, the stimulus type, the procedures used at focusing certain visual brain regions of dyslexic individuals, and poor experimentation techniques targeting a combination of processes rather than those concerned specifically with magnocellular function. The findings of a poor magnocellular pathway in Galaburda et al (1985) could have originated from brains of poorly categorized dyslexics having some form of developmental setback, acquired and genetic diseases (Galaburda et al., 2006), all of which could have manipulated the brain anatomy. In fact, some studies having used quite a smaller quantity of dyslexic (and control) participants have failed to replicate findings of a visual deficit (Amitay et al., 2002; Hulme, 1988; Skottun, 2000; Williams et al., 2003; Witton et al., 1998) previously observed by Lovegrove and colleagues, suggesting the need for a larger quantity of participants to authenticate the peripheral magnocellular impairment. Furthermore, not all dyslexic individuals were observed to suffer from magnocellular deficits, as a majority of dyslexic subsets actually did not show such visual difficulties (e.g. Tallal et al., 1980, 1984). Also, a series of papers reviewed by Skottun & colleagues (Skottun, 2000, 2010; Skottun & Skoyles, 2007) have strongly criticized the use of contrast sensitivity measures to access visual magnocellular functions (also see Goodboum, Bosten, Hogg, Bargary et al., 2012). For instance, of the 22 different studies Skottun (2000) reviewed pertaining to magnocellular functions in dyslexia, only 4 studies lent support towards a magnocellular deficit. Interestingly, Skottun & Skoyles (2007) proposed that a given study focusing upon the cortex could demonstrate visual deficits in dyslexia linking deficits to magnocellular together with some form of parvocellular input, thereby rendering it to be an "impure" magnocellular deficit (evidence from primate studies: e.g. Merigan & Maunsell, 1990, 1993; Merigan et al., 1991; Schiller et al., 1990). Moreover, Skottun & Skoyles (2004, 2006) stressed that sensitivity towards sudden directional changes (e.g. in motion tasks, Talcott et al., 2000) are neuronal processes concerned by and large in the visual cortex, and not the magnocellular system, whereby the latter could have actually been influenced by external processes not related to magnocellular processing. The use of coherent motion tasks in accessing magnocellular functions has also been criticized. Both these arguments are supported in a recent review made by Schulte-Korne & Bruder (2010) based on a collection of psychological studies measuring contrast sensitivity using motion processing tasks, in addition to other studies (Everatt et al., 1999; Sayeur et al., 2013; Skottun, 2005; White et al., 2006). Skottun & Skoyles (2008, 2011) further stated that magnocellular deficit was not causally related to dyslexia given this perceptual deficit was also common with individuals having various other disorders (e.g. schizophrenia, Martinez et al., 2013; and autism, Greenway, Davis, & Plaisted-Grant, 2013).

Interestingly, with studies having demonstrated a higher incidence of visual stress in dyslexic individuals leading to impaired reading fluency (Singleton & Trotter, 2005; White et al., 2006), some authors have posited that this symptom may be related to magnocellular dysfunction, since the latter was known for playing an important role in eye movement control (Christenson et al., 2001; Ray, Fowler, & Stein, 2005; Stein, 2001). Proponents of the magnocellular theory pursed the idea of using coloured filters to alleviate visual stress and thereby aid dyslexic individuals in reading (e.g. Stein et al., 2000; Lawton, 2008). For instance, Stein et al (2000) tested just the CwDys in an experiment tapping monocular occlusion using yellow filters as a means to aid reading fluency. The premise of this study was such that if a significant percentage of dyslexic individuals happened to experience some form of binocular instability, then a treatment would necessarily be of the form where one eye gets occluded for some time till the individual is able to achieve a fixed reference enclose. It was reported that the treatment group (spectacle having a yellow and an opaque lens) had stable fixations which developed significantly rapidly compared to the control group (spectacle each having yellow tinted lenses on both sides). Stein and colleagues attributed the pattern of progression in the control group to the yellow lenses "enhancing the magnocellular system". Ray, Fowler, & Stein (2005) in a follow up study reported findings of increased motion sensitivity when CwDys were subjected to wearing spectacles containing yellow filters. However, a majority of other studies have shown no evidence of any magnocellular dysfunctions related to visual stress in dyslexia (e.g. Albon, Adi, & Hyde, 2008; Cornelissen et al., 1998; Henderson, Tsogka, & Snowling, 2013; Ramus et al., 2003;

Roach & Hogben, 2004; Skottun, 2000; Sperling et al., 2005; Wilkins, 2003; Wright, Conlon, & Dyck, 2011). It is without doubt that the magnocellular, when compared to the parvocellular pathways, are relatively insensitive to colour (e.g. Roorda & Williams, 1999; Nandakumar & Leat, 2008). It has been previously shown that participants with no reading deficits have also benefitted following the use of such filtered lenses (Jeanes et al., 1997). In addition, studies assessing a group of CwDys in an ocular accommodation task have reported fewer benefits for those who regularly used coloured lenses in an attempt to improve their reading skills (Simmers, Bex, Smith, & Wilkins, 2001; White et al., 2006). In some cases, the AwDys reported far more frequent symptoms of visual stress[3] than compared to adults without dyslexia. This is in addition to AwDys having reported less favourable progress with regards to the level of reading improvement (i.e. no improvement in both reading comprehension and reading rate for connected text) following the use of overlaid lenses (Henderson, Tsogka, & Snowling, 2013). Having already familiarized that other magnocellular deficits are also found in certain dyslexic individuals even in the absence of reading disorders (Skoyles & Skottun, 2004; Vellutino et al., 2004), this itself is an evidence against the magnocellular theory of coloured filters' assisting CwDys with reading impairments. Additionally, Castelo-Branco et al (2007) had reported findings of magnocellular deficits in Williams Syndrome, with some displaying a total lack of behavioural and perceptual benefits. According to some critics, these sensorimotor deficits are thought to be more of a associated factor, rather than a cause, of dyslexia (Ramus, 2003; Vellutino et al., 2004; White et al., 2006), yet it is hardly convincing that such deficits point towards magnocellular impairments (Amitay et al., 2002). In fact, Skoyles & Skottun (2004) stated "not only are there cases of dyslexia that are not attributable to magnocellular deficits, but also there are a substantial number of instances of magnocellular deficits that do not lead to dyslexia" (p. 81). Visual stress therefore remains a controversial subject, with these findings further questioning the use of coloured overlays/filters/lenses for the purposes of detection and/or treatment of visual stress as a way out for reading difficulties in dyslexia.

The magnocellular system is also known to be important for directing visual attention. Some studies have observed the magnocellular pathway extending to parts of the ventral visual stream with projections reaching the right PPC, an area known for visuospatial attention modulation (Vidyasagar & Pammer, 2010). Any shortcomings with regards to the

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[3] Visual stress (also known as Irlen syndrome, Simmers, Bex, Smith, & Wilkins, 2001) is a condition where an affected individual finds it hard to view visual images or written text whilst experiencing some form of visual distortions (e.g. changes in movement, sudden flickering, jumbling of text, blur and illusions of colour) and rotations within the periphery (Wilkins, Huang, & Cao, 2004). This is usually accompanied with discomfort and symptoms such as headaches, dizziness, nausea, seizures and tired eyes (Wilkins, 1995; 2003).

incoming magnocellular input therefore prevents an individual from being able to deploy spatial visual attention crucial for analysing single words. A visual attention deficit of this nature undoubtedly turns out to be a contributing factor towards reading weaknesses observed in dyslexic individuals (e.g. Hari et al., 1999; Iles et al., 2000; Stein & Walsh, 1997; Vidyasagar, 2004; Vidyasagar & Pammer, 1999). One study which has utilized both magnocellular and visual attention to some level of appreciation is that of Sperling and colleagues (Sperling, Manis, & Seidenberg, 2005, 2006). They studied the effects of coloured filters for reading in dyslexic individuals on an entirely different magnitude based on a "noise exclusion" deficit. "Noise" in this case refers to information which negatively influences the decision process. Sperling et al (2005) assessed the contrast sensitivity function between CwDys and age matched controls using a visual stimulus (alternating white and black gratings in the presence/absence of a static white noise) known to specifically activate magnocellular and parvocellular pathways. In the presence of noise, dyslexic participants exhibited significantly elevated contrast thresholds when detecting the signal. Sperling et al (2006) came up with similar findings for both C&AwDys by utilizing a random-dot kinematogram task, in that, both groups performed identically in the absence of noise, unlike where dyslexics needed significantly elevated consistency (at high noise) when familiarizing the dots prior to its motion. Sperling et al (2006) concluded that problems in extracting relevant stimuli from irrelevant noise in dyslexic individuals to be a potential cause of dyslexic symptoms, unlike a magnocellular deficit. These findings prompted Northway, Manahilov, & Simpson (2010) to directly test the capacity to which AwDys and their control counterparts were able to discriminate a symbol under varying noise conditions whilst wearing 3 types of filters (control dummy, neutral density and optimal coloured - Wilkins, 2003). Findings showed that dyslexics, compared to controls: (i) had longer discrimination times in the noise condition, (ii) had better performances with the optimal filter in the noise condition, and (iii) showed no significant differences to their counterparts in the no noise condition – all of which were consistent with that of Sperling & colleagues (2005, 2006). Moreover, the discriminative performance of participants correlated significantly with reading ability in the presence of elevated noise conditions (Sperling et al., 2005, 2006), with findings attributed to a noise exclusion deficit accounting for reading difficulty in dyslexia. It is thought that a defective system of this nature could seriously affect visual processes such as visual–orthographic analysis of words resulting in poor letter and letter sequence recognition, identification of word shape and inter-word boundaries, all of which could therefore lead to weak phonological representations. Importantly, these visual processes eventually depend on proper functioning of a visual attention system (e.g. Ruffino, Gori, Franceschini, & Facoetti, 2010). In essence, poor reading in dyslexia is not a direct consequence of a visual deficit. Instead, it is much more of an extensive predicament influencing a whole array of other major visual functions. Based on this view and those mentioned with other dyslexia theories, attention therefore becomes a means to tie all the findings together in dyslexia. The next section focuses on the attention component of dyslexia within the visual modality (specific to the main theme of the present thesis).

1.6 Visual Attention Theory

1.6.1 Introduction to Visual Attention

Every time we use our eyes to perceive the world around us we are bombarded with an overpowering quantity of visual information, but we are still able to gracefully appreciate our surroundings. For instance, imagine a scenario where you happen to be in close proximity to a life threatening source (e.g. fire) but hardly are you aware of it in the first place. Upon automatically spotting a blaze at a given peripheral location not in the immediate vicinity of your central gaze, the normal reaction would be to act swiftly so as to ward off from this particular dangerous source. This behaviour is made relatively easy thanks to the visual attention system which has evolved in such a way that its focus gets diverted towards the most essential piece of incoming information. With all the other instinctive functions competing for memory processes at the same time, there are significant limitations imposed on the processing capacity. Such limited processing capacity entails attention selection considering the preciseness of its source (i.e. ability to discern between relevant and irrelevant information), the means of selection (i.e. early or late), along with the fate of both selected and unselected information. Going back to the scenario, such an environment would typically present many competing visuals from hazardous sources for which one must first select the most relevant visual concerning the nearest source of hazard. In other words, selection is achieved by the attention system prioritizing some facets of the salient information in the process of ignoring irrelevant ones, all this whilst focusing on one given aspect of the visual scene. The next most important step is modulation, the extent to which the selected representation eventually gets processed, i.e. how quickly and precisely both the task and response functions are performed, and how well the event gets stored in the memory for future retrieval. In the scenario, one would have to keep track of the most dangerous hazard (while scurrying away from it) in addition to other potential hazards on the way. For such a process to happen smoothly, the observer should be able to sustain attention by focusing on the main hazardous threat whilst actively searching for others over a stipulated period of time. Based on this scenario alone, there are several important attention processes to consider as summarized in the following order of importance: (i) attention selection, (ii) focusing and allocation of spatial attention, (iii) attentional visual search, and (iv) attention modulation. My next aim is to have a quick overview on each of these mechanisms and functions in typically developing individuals.

1.6.2 Selection Theories of Attention

In a complex task such as reading, there is a need to consciously accommodate visual information arriving at varying time stamps and from sequentially ordered positions of a page. It becomes immediately apparent the important role played by eye movements in such a complex task. As surprising as it may seem, however, eye movements do not add up towards the overall selection process. When it comes to attention selection in reading in an attempt to aid goal directed actions (e.g. to spell out a word from a sentence of text), the incoming visual information is expected to undergo some form of "filtering". Essentially, the filtering process is what is considered to be one of many important functions of the visual attention system. Using simple filtration paradigms, studies have manipulated one element of a task (selection criterion) whilst leaving certain other elements intact (stimulus display and report feature) in order to access the selection capability. Eventually, it comes down to three important and most influential attention theories, namely early selection (Broadbent, 1958), late selection (Deutsch & Deutsch, 1963), and the load theory (Lavie, 1995) which helped shape the understanding of the perceptual aspects of attention selection. Both the attention theories (early and late) were subjected to extensive debate based on how early/late this filtering mechanism was involved and the extent to which irrelevant information was eliminated from additional processing. The next few sections focus on these theories in an attempt to bring out some of the key components of attention. This would therefore complement the studies carried out within dyslexic populations (**section 1.6.6**). For the sake of simplicity, I intend keeping these sections very short with the key focus laid on just a few studies.

1.6.2.1 Early Selection Theory

Early selection theories presumed that attention filtering of irrelevant information occurred immediately following the appearance of the visual information. The explanation to this came from Broadbent's (1958) filter theory of attention. Broadbent hypothesised that it comes to a particular position within the processing hierarchy where features pertaining to all incoming sensory information (be it auditory or visual - "S") are examined and represented. Based on the processing machinery that identifies a particular stimuli (e.g. to recognise a letter/word so as to understand its meaning), Broadbent claimed that it could only process a single stimulus at any one given time. The stimulus having the presidency to undergo further processing thereafter depends solely on salient stimulus features to which the filter is attuned to, the type which he referred to as the selective filter. According to his view, selection is expected to happen during early stages of signal processing. This was further elaborated using structural box diagrams to explain the order of selection incorporating a time frame (**figure 8**).

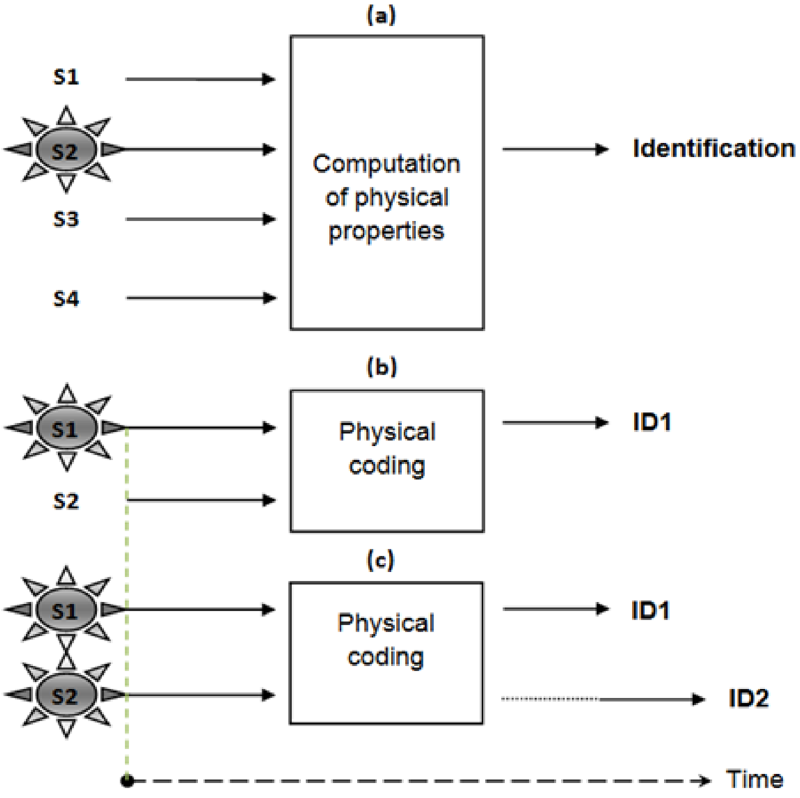

Figure 8: Early selection theory of attention. (**a**) Computation is carried out based on physical properties of all the stimuli but only attended stimuli becomes eventually identified. (**b**) For several stimuli arriving at various sensory receptor machinery ("S1", "S2"…), soon after it gets recognized the internal representations becomes identity labelled ("ID1", "ID2"…). In the first instance, the attention mechanism identifies the stimulus features of both S1 and S2 and thereafter processing the identity of just S1 alone. (**c**) In the case of two stimuli being attended, both gets to undergo recognition but it happens that soon after identity labelling, either both S1 and S2 gets processed individually (serial processing, ID1 then ID2) or in parallel (parallel processing, ID1 along with ID2). [Source: Adapted from Pashler (1997)].

The earliest study into selective attention was conducted by Sperling (1960) inspecting the limits to processing capacity of the visual attention system. Participants were asked to observe a concise visual stimulus display containing a maximum of twelve stimuli (containing both letters and/or numbers) referred to as the "whole report". When asked to report the as many number of stimuli as possible, the participants managed to name a maximum of four to five items prior to offset of the stimulus screen, suggesting the presence of a capacity limit based on the information retrieved. This prompted Sperling to introduce what he referred to as the "partial report" technique which provided a measure regarding both the availability and the overall duration of storage for the visual image to follow after stimulus offset. In addition, one of three auditory tonal cues of various frequencies (low, middle and high) was sounded immediately after stimulus offset, with each tone characteristic of a given particular row (out of three) of visual stimulus that needed reporting. Since these tones and accompanying visual stimulus were fully randomised, the participants did not have the opportunity to anticipate a given signal. Based on the findings reported, participants exhibited a significantly higher accuracy of recall only in the cued condition, in addition to them being able to report the stimulus up to 150 msec following stimulus display offset. Sperling suggested that cueing enabled the participants to (i) recognize all the twelve stimulus items, and (ii) recall a subset of the display. This finding was consistent with that of Broadbent’s account, i.e. limited capacity and an early selection of visual attention. One add-on feature as far as Sperling was concerned was that of internal representation, where he suggests the possibility of the target stimuli having been represented in both the perceptual and memory systems, thereby paving way for information to be selected at an early stage.

In an attempt to verify the exact location of visual processing, studies have also pursued with partial reports in various cueing paradigms. Using a masking paradigm[4], Bjork & Murray (1977) employed the use of a pre-masked template (indicating the stimulus location to be remembered) following which a couple of stimuli were presented with one corresponding to the relevant (henceforth referred to as the "target") location. Shortly afterwards, a post-mask was presented requiring participants to report the cued target (e.g. S or R). The accuracy of detection was observed to be significantly shaped by the

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[4] Masking here refers to the damaging effects which one stimulus has thereby affecting the sensitivity of another. For example, consider a visual stimulus (where in normal conditions becomes easily recognisable) that ends up being unrecognised by a processing machinery. Two ways in which this could happen, a condition when another stimulus competes along with the stimulus in question within the same visual field (backward masking), or it could be that the other stimulus happens to be located closest to the stimulus in question (lateral masking). In both these conditions, masking avoids identification of a target stimulus in spite of the observer being able to attend to the target whilst making every effort to ignore the masking stimuli.

irrelevant (henceforth referred to as the "distractor/s") stimuli present alongside the target. That is, speed and accuracy of detection was observed to be on the higher side when the target and the distractor stimuli were both dissimilar (e.g. S , R) compared to them being similar (e.g. S , S). This was in line with the suggestion previously made by Sperling (1960) confirming that the information pertaining to the target items undergo internal representation, an evidence of early selection of attention, since the information coming from distractors were excluded without any further processing. As a result, this provides ample selection of relevant information at an early stage. Particularly key to this understanding is the dominant role played by stimulus timing and internal representations, both of which are expected to modulate distractor interference.

1.6.2.2 Late Selection Theory

The explanation to this theory came from a multiple set of authors (e.g. Deutsch & Deutsch, 1963; Eriksen & Eriksen, 1974; Shiffrin & Schneider, 1977). They commonly stated that recognition of common objects advanced indiscriminately devoid of any capacity limitations (**figure 9**). That is, irrespective of the number of incoming sensory inputs, there is no influence whatsoever on the extent to which they are analysed free off any time frames. Based on this stance, it was presumed that attention filtering of distractor information occurred only after all the information had undergone complete processing (semantic analysis). This was based on the fact that all incoming information ends up being processed, despite whether or not attention was engaged to it. Treisman (1960) initially demonstrated information with the least relevance towards specific goal directed tasks to be processed, despite not having an impact on the overall task itself. Treisman utilized a dichotic listening task subjecting participants to a series of 4 spoken passages, with these being suddenly swapped around in the latter half of each session, with participants required to ignore the passages appearing in one ear, whilst repeating the passages appearing on the other. It was reported that participants (i) intermittently switch the ear they were repeating while ignoring that in the opposite ear, (ii) repeat a few couple of words based on the unattended ear, but on realizing this mistake they were able to redirect their attention to the attended ear, and (iii) are deprived (but not fully restricted) when required to swap passages. Treisman (1969) replicated the same study in the visual attention system incorporating physical properties of visual stimuli which included colour and location related information. Then again, similar findings were found with participants having no difficulties in selecting the basic properties of the visual system at a much early stage, with the exception of the distractor information being constricted, rather than being completely filtered. Treisman suggested that the information from the distractor source had undergone some degree of semantic analysis, the reason why she believed that participants responded much slowly in the swapped condition, further adding that these findings confirmed just how closely the stimulus quality influenced the degree of distractor interference.

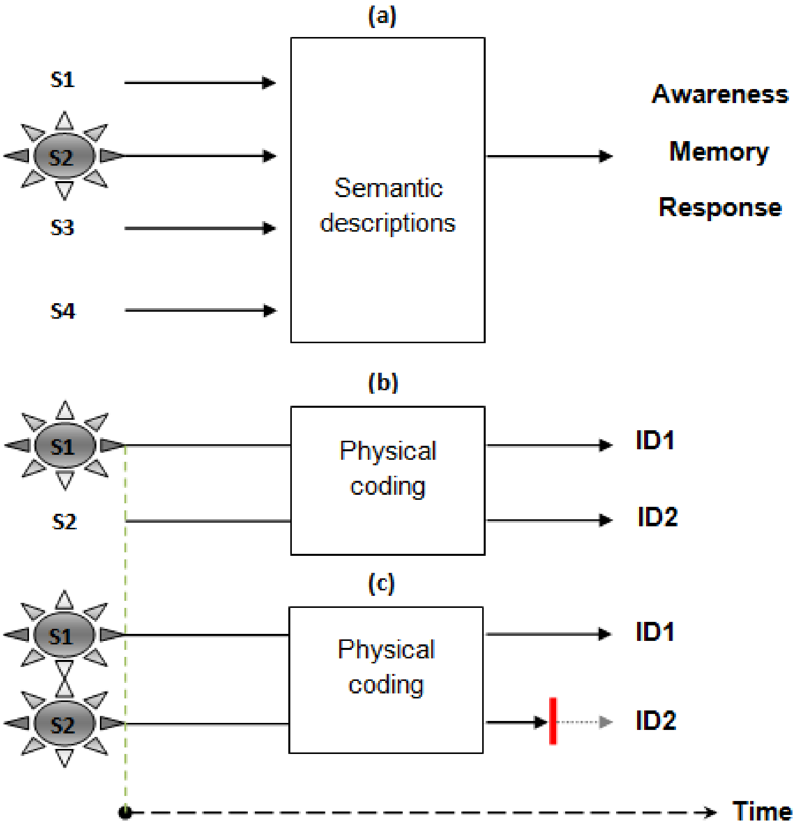

Figure 9: Late selection theory of attention. (**a**) Computation is carried out based on identity of all the stimuli but only attended stimuli gets selected by the system required for processes such as awareness, memory and response. (**b**) For several stimuli arriving at various sensory receptors, the attention mechanism identifies the stimulus features of both stimuli thereafter processing the identity of both. (**c**) In the case of two stimuli being attended, both gets to undergo recognition but the one which is considered to be most advantageous (ID1) is processed further. [Source: Adapted from Pashler (1997)].

Studies further extended to measure the maximum level of distractor interference via the manipulated use of both the target and distractor stimuli in a response competition paradigm (Eriksen & Eriksen, 1974). Based on this paradigm, they devised a visual "non-search" task (i.e. the appearance of a target at the same location throughout all trials) and in doing so they verified the extent of distractor interference based on the performance required to process the distractors when the tasks were mapped specific to a stimulus response (i.e. using specific lever movements, **W** and **X** mapped onto 1 response whilst movements Y and Z mapped on to another). It was reported that participants had slower reaction times especially in conditions when the targets had incongruent response mapping, i.e. X**W**X compared to Y**W**Y or Z**W**Z (note the distractors "Y" and "Z" from opposite batch). The authors referred this as a distractor compatibility effect whereby distractor interference from the opposite batch of responses produced slowed reaction times significantly more than the same response distractors, which prompted the authors to suggest that the information regarding the target was distinguished from the distractors only during the later stages (i.e. during selection of a particular response) despite processing most of the available information.

The finding based from Eriksen & Eriksen (1974) was further supported by a large scale study carried out by Miller (1991) who focused on some of the key issues which he thought was solely responsible for processing of the distractor stimuli: i.e. (i) the resolution of spatial attention, (ii) the length of time taken to focus attention at a fixed location, (iii) the quality of attention fixation when guided towards a blank display location, and (iv) exclusion of distractors during semantic processing, based on conditions lacking demand by the attended items. Miller reported that the distractor compatibility effect was obtainable with just 5° of visual angle isolating the distractors from the target. Moreover, on increasing the visual angle there were changes observed with regards to the size and the type of effect, both which occurred either directly or following changes in the duration between target-distractor detection, suggesting that distractors are sometimes processed despite being located quite a few degrees away from the target. Therefore, based on this finding Miller emphasised that visual information concerning the distractor(s) was not entirely excluded from semantic processing, despite it being a real disadvantage when accomplishing a task. In particular, the distractors which were observed to tag along during semantic processing provided solid evidence that individuals were unable to limit their visual attention to one specified portion of the stimulus display. Miller attributed this distractor compatibility effect to a function of attention selection taking place at a late stage of processing (following perception of all stimuli). Comparing his finding with that of Broadbent’s (1958), Miller concluded that early attentional selection was unable to exclude distractors entirely from semantic analysis.

1.6.2.3 Load Theory of Selective Attention

Load theory of attention (Lavie, 2005) looks at attention selection by applying a capacity approach to infer the changes brought about by selective attention on visual perception.

The load theory of attention centres on the influence that a certain quantity of incoming visual stimuli has on attention selection system and the extent of distraction generated as a result (Lavie, 1995). Based on the load theory, one of the key selective mechanisms of attention is that of an involuntary passive-perceptual system which is of limited capacity. It operates selectively when attending to visual stimuli (linguistic and non-linguistic) based on the quantity of available information at any one time. In the presence of information arriving from a large influx of visual stimuli (high perceptual load), capacity to process information would be minimum due to the exhaustion of its reserves following the processing of the attended information, thus resulting in the lack of perception on the part of unattended information. That is, for 5 potential target stimuli and one distractor competing with 5 channels, the chances of perceiving the distractors are minimal as the targets fully consume the available attentional resources. In contrast, for tasks taxing low perceptual load (e.g. 5 channels, for which 1 potential target stimuli and 5 distractors are presented), both attended and unattended information ends up being processed until all the attentional capacity gets used up. Given the spare perceptual capacity to begin with, 4 out of the 5 distractors are more likely to be perceived as sufficient capacity spills over for the uptake of distractor information. Therefore, at a state of low perceptual load, distractor information generally results in interference as attentional selection occurs in the late stages of visual processing, i.e. attention operates non-selectivity during low perceptual load, whilst operation occurs selectively at high load conditions (Lavie, Beck, & Konstantinou, 2014; Lavie & Tsal, 1994). This goes to show the relative importance in being able to retain not only the task information relevant to a particular goal (properties of task-relevant vs. irrelevant stimuli), but also the ability to prioritise at high perceptual load (Lavie, Hirst, De Fockert, & Viding, 2004) both of which are crucial for optimum selective and focused attention.

Earliest studies used measures of distractor interference based on task reaction time to estimate the influence of perceptual load on attention control and perception. By manipulations such as increasing either the number of stimuli presented on a stimulus display (the term referred to as the "set-size") to be processed, or increasing the complexity of perceptual function of a task (whilst keeping the set-size constant), many authors have succeeded in amplifying the perceptual load. Lavie and colleagues carried out several experiments investigating whether perceptual load modulated the distractor interference effect in attention selective visual tasks (Lavie, 1995; Lavie & Cox, 1997; Lavie & de Fockert, 2003; Rees, Frith & Lavie, 2001). In an attempt to inspect the functional capacity of the perceptual load, Lavie (1995) utilized the response competition paradigm to evaluate distractor interference. Perceptual load was controlled by randomly altering the stimulus set-size, i.e. a single target letter was presented in one of six stimulus locations with only the target stimulus presented in low load conditions, compared to a target and five non-target letters being presented at high load conditions (**figure 10**). At low load conditions, reaction times of target detection were reported to be fastest on trials containing compatible items (both target and non-target are *x*), and slowest on incompatible items (target as *x* and non-target as *z*), which suggested facilitation effects caused by compatible distractors whilst incompatible distractors caused interference effects. No significant differences across distractor type was reported for high load conditions, suggesting that the attention system had a poor ability to exclude low-priority items from undergoing perceptual processing given the increased demands for attentional capacity. Moreover, Lavie & Cox (1997) varied the similarity between targets and distractors to induce variations in search load under two task difficulties, easy (low load) and hard (high load). Findings showed significantly slower reaction times in the easy/low perceptual load compared to the hard/high perceptual load search task. This suggests that the reduced distractor interference effect at high perceptual load to be a result of poor prioritization for difficult tasks. Using similar studies of this nature, Lavie demonstrated that an increased perceptual load demanding greater attentional resources led to far more efficient elimination of distractor processing. Several other studies have also found findings consistent with that of Lavie (e.g. Cartwright-Finch & Lavie, 2007; Lavie, 2010; Tsal & Benoni, 2010) despite a few alternative accounts tapping effects of perceptual load with target saliency. For instance, with the target appearing more salient than the distractors, Eltiti, Wallace, & Fox (2005) demonstrated distractor interference at high load, suggesting that factors external to processing capacity may influence distractor interference.

With studies having demonstrated that focusing visual attention tends to result in less processing of distractor items (e.g. Lavie, 1995), a handful of few studies have in fact utilised this idea to extend findings into visual attention orienting deficits in dyslexia. For instance, Facoetti & Molteni (2000) performed a choice reaction time task where a central coloured (green or red) dot was surrounded by a distractor (letter) on both the left and right side based on its compatibility towards the type of response (response-compatible or response-incompatible dot, both of which were denoted by dot's colour). With each trial initiated by either a 0 or 500 msec SOA central circular dot stimuli, a central cue (either small or large) was presented requiring participants to respond towards the appropriate task compatible colour. The authors reported findings of faster responses during compatible unlike incompatible trials (the term referred to as the flanker effect) that too only in the presence of the smaller cue presented at 500 msec SOA. They concluded that

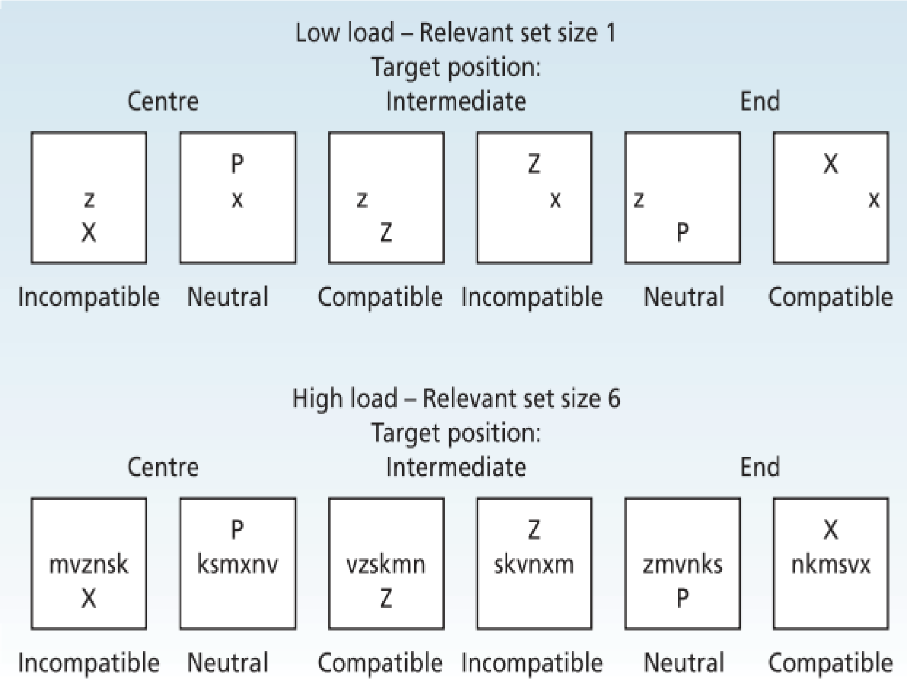

Figure 10: Perceptual load and distractor interference effects. Displaying stimulus types employed by Lavie. [Source: Adapted from Lavie (1995)].

constraining visual attention is time dependant, i.e. at shorter durations (at 0 msec SOA) neither cue type had any effects of disparity given the lack of time needed for attention to confine its functions to that cue, whilst with the longer duration (500 msec SOA) attention was able to confine itself to either of the two cues with ease, suggesting the difficulty that dyslexic individuals had when eliminating the distractors when included within a larger cue unlike with the smaller cue. This finding therefore raises a question as to whether a limit such as this is entirely capacity dependant based on how participants are made to focus their attention.

It therefore becomes even more interesting to know the process best describing that in the absence of a cue altogether, with participants still requiring to limit their visual attention. This answer to this question came from Facoetti et al (2003) having demonstrated an impaired visual attention focusing ability in dyslexia. This study was same as that in Facoetti & Molteni (2001), with the exception of the minimum SOA being 100 msec, in addition to a pointed arrow target. Facoetti and colleagues attributed the lack of cueing benefit at 100 msec in line with a sluggish orienting of visual attention arising due to a limitation in attention controlling ability. When it comes to reading, dyslexic individuals are known for their enduring problems with limiting visual attention (i.e. excluding information from peripheral regions while maintaining foveal fixation). Such deficits are even more pronounced when carried out in dyslexic populations with the added influence of interference based set-size effects, i.e. word length based on the number of letters (e.g. Ghahghaei, Linnell, Fischer, Dubey, & Davis, 2013). Hence, for dyslexic individuals, the task of reading exerts a heavier load on visual attention compared to controls especially when it comes to nonword and pseudo-word reading (both which consists of unfamiliar syllabic structure). The effects of perceptual load are such that, active management of process is necessary when orienting the attention independent of saccades given the constant shifting of the attentional focus. Should the (fixated) target word demand much higher perceptual resources, attention in the absence of saccades should end up being selectively focused on the word, thus delaying the disconnection from the fixated word. This results in the postponement of both attention reorienting and saccade towards the next (target-to-be) fixated word (Rayner, 2009). However, this is completely opposite in skilled readers where scanning of a given set of text happens effortlessly with much greater fluency despite the word length, with the difference in performance reflecting the ability of skilled readers to narrow their attentional focus, thereby aiding them to identify each letter in a given word with ease.

In summary…

With regards to both the early and late selection theories of attention, the former explains that information regarding distractors may end up being excluded from further processing at a very early stage. However, the latter proposes that information regarding both the distractors and the target are subjected to complete processing such that selection of target information takes place at a much later stage. In addition, both theories differed based on how they accounted for distractor interference effects. In early selection, distractor interference effects were accepted as a deficiency with regards to visual attention system in being unable to exclude information concerning distractors. In late selection, the distractor interference effects were accepted as an outcome due to complete processing of information coming from both the target and distractors. That is, the visual attention system is capable of sustaining some degree of distractor interference effects at the expense of an overall slow functioning attention system. Despite the broad range of studies conducted, the disputes encircling the precise or near-precise site of selective visual attention remains pretty vague. The load theory of selective attention mentions a key perceptual process accountable for distractor exclusion. The extent of distractor interference was investigated by means of various experimental manipulations. Perceptual load theory provides a proposal concerning the site of visual selective attention by linking both the early and late selection theories.

The next section focuses on visual attention types and the experimental paradigms used within control populations, their functional importance, along with the mechanisms to combat efficient distractor interference. The focus then leads into the dyslexic population.

1.6.3 Types of Visual Attention

The one reason which makes attention multifaceted in its own right is due to its main features common to various visual systems. The problem however is the advent of excessive information which requires hardcore processing. The solution then becomes even complex at instances when there is a genuine need for selection and modulation of information based on that which is most appropriate for a given visual action. Then again, the challenge is to constantly aid processing of what is most important and excluding that which is not, all this of course while sustaining alertness towards a goal-directed action. With features such as these complementing several types of visual attention, it would be ideal to categorize them individually according to the kind of information arriving from their targets.

There are two major types of information to which we are all constantly bombarded which requires selection. On one hand, the information that comes to an observers mind from various sensory modalities with intermittent time and location specific labels requiring selection and modulation is referred to as "external attention" (e.g. conversations happening around an observer). On the other hand, information which is mentally created (ongoing memory processes within the long-term and working memory, active cognitive supervision, and choice of responses) requiring selection and modulation is referred to as "internal attention" (e.g. identifying the familiarity of those talking). By having to concentrate on one specific source of input so much so that the other input is subjected to exclusion, this type of attention is referred to as "focused attention" (e.g. reading a piece of text while ignoring the vocal news bulletin over the radio). Suppose more than one source is attended at any one given time, the information which eventually gets selected is somewhat incomplete, the term referred to as "divided attention" (e.g. while following both the newspaper and the radio bulletin). The loss of information in a divided state of attention is due to the two information sources competing for common attention resources. Given the limited capacity of resources available, task(s) demanding more than what is available eventually leads to task limitations and failures. Attention process which are undertaken voluntary by nature and that which is also top-down (i.e. derived from previously acquired knowledge) is referred to as "endogenous attention". In fact, process where the visual attention system had innately captured the stimuli, generated external to an observer, in a bottom-up fashion is referred to as "exogenous attention". Some of these mentioned attentional types are also known to be further subdivided as spatial, temporal and object forms of attention deployed over both space and time. Spatial attention can be either feature or object based. Feature based attention is one which gets deployed covertly towards explicit target features (e.g. orientation, colour, etc) independently of their location, while object-based attention is when attention gets directed by a specific target configuration. By having to focus on a diverse set of visual information at various time points, these attention types optimize our visual system in a way the observer is able to subjectively differentiate a target stimulus from distractors (Carrasco, 2011).

The study into spatial attention was first carried out by Posner where the focus of spatial attention was described as an internal spotlight (Posner, 1980) or zoom lens (Eriksen & Yeh, 1985). This was known to intensify the visual processing of a given stimulus arriving from a limited area or spread across space, the former generally yielding an enhanced effect (Jans, Peters, & De-Weerd, 2010). Given the large volume of incoming spatial visual information from ones surroundings, spatial attention is responsible for prioritizing these "information packets" so as to guide and deploy relevant eye movements (foveal acuity) needed for perception (Rayner, 2009). Eye movements (saccades) are therefore closely coupled with spatial attention, despite the former being second to a process more complex as attention filtering. Both spatial attention and saccades functions either dependently or independently from one another, in that, spatial attention can either guide saccades in an overt manner (voluntary), or it can attend to a given location in the absence of saccades in a covert manner (involuntary). Using specific task related exogenous and endogenous cues studies have been able to modulate both overt and covert attention, thereby improving the detection and discrimination of targets from surrounding distractors (e.g. Posner, 1980; Yantis et al., 2002). The voluntary orienting of attention is achieved via a goal-directed fashion, whilst involuntary orienting occurs predominantly in a stimulus driven fashion. The temporal characteristics of the cue have been further attributed to two other forms of spatial attention, namely transient and sustained attention. A cue when presented 100 – 120 msec prior to the stimulus array (containing the target and distractors) facilitated a greater degree of involuntary attention resulting in a transient effect (i.e. known for operating over shorter durations with rapid decay, e.g. Ling & Carrasco, 2006). In contrast, a cue presented 300 msec prior to the stimulus array facilitated ample time for voluntary deployment of attention resulting in a sustained effect (i.e. known for operating over longer durations with smaller intensity, e.g. Liu, Stevens, & Carrasco, 2007). In this way, spatial attention assists in processing of incoming stimuli from attended locations while inhibiting distractors from surrounding locations. Immediately after focusing attention to a cued location, reorienting or shifting of attention thereby ensures that accurate and precise deployment of attention is carried out to a new location in space.

Studies into visual temporal attention were demonstrated in studies employing attentional blink paradigm, with its focus concentrated on stimuli arriving at various time intervals within the same location (Jolicoeur, Sessa, Dell'Acqua, & Robitaille, 2006). Although temporal attention experience the same features as that of spatial attention, unlike the latter, temporal attention is untroubled by the impedance caused by dual tasks (Correa & Nobre, 2008). An important point to note here is that the temporal attention is restricted based on the quantity of incoming visual stimuli both in time and space (despite being fully attended). However, the way in which temporal attention conquers this constraint is by selecting task appropriate information resulting in a slowed processing rate. Studies of this type require individuals to search, retain and report one or two targets in the midst of several other distractors presented in quick succession at one common location. The ability to retain and report targets is reported to be severely inhibited in the second stage when searching for more than two targets (Broadbent & Broadbent, 1987; Shapiro, Driver, Ward, & Sorensen, 1997). The higher performance in the first stage strengthens representations of the previously seen targets into awareness required for the second stage, the process which was aided by the working memory involving the fronto-parieto-temporal pathway (Dehaene, Sergent, & Changeux, 2003).

In addition to spatial locations and various points in time, visual attention is also capable of being directed exogenously towards object features (modality specific, e.g. colour, pitch, orientation, etc). One other mechanism of attention operation in addition to that mentioned above is via feature saliency, i.e. how one given item (usually the target) is made more conspicuous than the other (distractor) defined by the extent of target-distractor similarity. The modulation towards attention of object features occurs in groups of neurons located at feature-dependent regions of the cortex (Kanwisher & Wojciulik, 2000). For example, changes in stimulus orientation (e.g. Gabor patches) during selective attention sparks a simultaneous increase in orientation processing, which goes on to further influence the contrast sensitivity in the layer four of the visual area (V4 in the extrastriate cortex, an area known for the tuning properties of orientation - McAdams & Maunsell, 1999). Further orientation processing is subsequently carried out within the visual cortex (Liu et al., 2007) and visual area V5/MT (middle temporal, a region within the extrastriate visual cortex), the latter known for its major function in motion processing during feature attention (O'Craven et al., 1997). Feature based attention on more complex stimuli (e.g. faces and objects/locations) have been observed producing significantly greater activation patterns within face (face fusiform area, FFA - within the ventral occipito-temporal cortex) and object/location-specific (para-hippocampal place area, PPA - ventromedial cortex) regions of the visual cortex (Kanwisher, McDermott, & Chun, 1997;

Haxby et al., 1999). Unlike spatial attention, feature based attention is spatially unlimited such that features belonging to various stimuli outside the attended location undergoes significant enhancement (Martinez-Trujillo & Treue, 2004). The neural pathway governing both feature and spatial selection entirely rests on the frontal-parietal network where attention is believed to enhance efficiency by lowering noise outside the limits anticipated from the coarse visual input (Mitchell, Sundberg, & Reynolds, 2009).

1.6.4 Classic Experimental Paradigms in Spatial Attention

1.6.4.1 Spatial Cueing Paradigm

Several studies in the past have attempted ways to understand the dynamics between overt and covert spatial attention modulation. Posner and colleagues were the first few investigators who utilized both exogenous and endogenous cues in a simple cueing paradigm to investigate spatial attention (Posner, Snyder, & Davidson, 1980; Posner, Strike, Hewson, & Gertzog, 1982). A cueing paradigm consists of a set of displays with task-specific stimuli (target and distractors) whereby individuals are required to respond as accurately and quickly as possible to a given target stimulus. Prior to the presentation of the target stimulus, an individual becomes subjected to a visual "cue" (also known as a pre-cue) which draws attention to a particular location in space where the target was expected to appear, compared to an un-cued display. This is shortly followed by a stimulus screen (containing a single target surrounded by distractors) after which the individual is expected to detect (button press following immediate detection of target – reaction time measure) and/or discriminate the target stimuli (choice of two buttons reporting whether target was X or Y – accuracy measure). The type of cues presented varies from study to study ranging from a simple outlined object to a symbol such as a dot or an arrow (e.g. Posner & Cohen, 1984). In many of the studies conducted by Posner and colleagues, the cues were presented either centrally (overt) or peripherally (covert) both which automatically deploys attention to a certain target location (**figure 11**). The paradigm further allowed manipulation and the comparison of various cue types according to its validity, i.e. valid (cue which correctly predicts the target position), invalid (cue which misleads observers to a wrong target position), or neutral (cue which is uninformative regarding target position) trials. The combined presentation of both cue and target SOA was preferred less than 250 msec (which is roughly the time taken to program and execute goal directed saccades, Mayfrank, Kimmig, & Fischer, 1987) by many investigators so as to ensure that covert spatial shifts of attention are free of cued eye movements, whilst other studies explicitly monitored eye position to ensure that fixation does not deviate from central fixation.

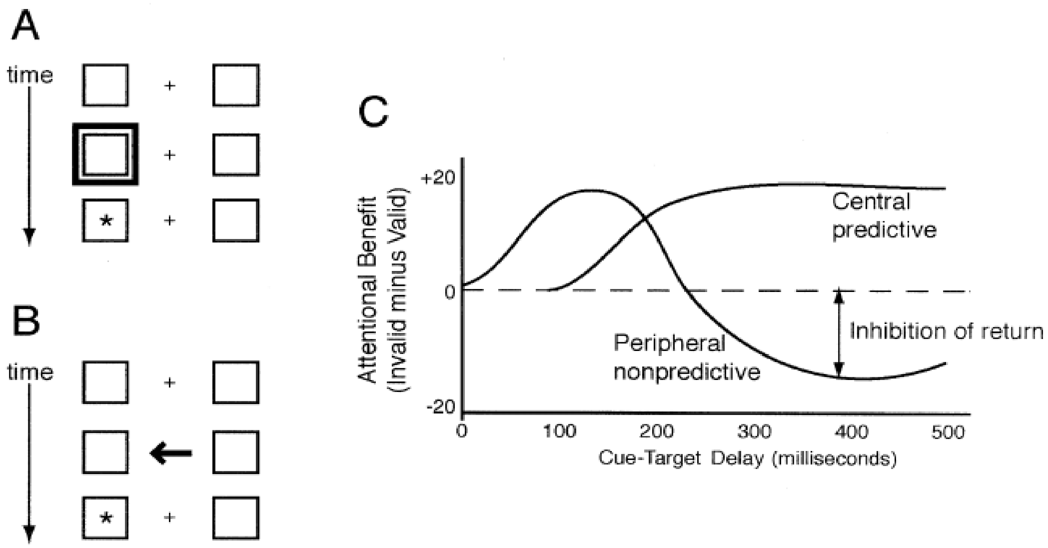

Figure 11: Sequence of events in Posner's spatial cuing task. A blank fixation followed by a cue display and finally a cue plus target display. The (**a**) peripheral pre-cue (outlined) and (**b**) central pre-cue (arrow) indicates precise target position (100% valid). (**c**) Graph showing the difference in response times (valid and invalid trials) with data indicating a period of inhibition (IoR) preceded by an early attentional benefit. [Source: Adapted from Vecera & Rizzo (2003)].

The outcome of such studies investigating spatial attention has indicated the level of attention control in typically developing individuals. Early studies reported evidence of both peripheral and central cues controlling attention differently (Jonides, 1981). Although the attention shifts provoked by central cues happened to be under active conscious control (with individuals assigning sufficient working memory resources) whilst the cue remained valid. However, in such a state it was extremely difficult for the same individuals to ignore peripheral cues (Giordano et al., 2009). In addition, the peripheral cues had very faster operational speeds in guiding attention than did central cues, although the influence of the former was neutralized by the presence of a central/neutral cue (e.g. Muller & Rabbitt, 1989). Based on these findings, both endogenous and exogenous attention revealed better performance with faster detection times in the order of cue type, i.e. significantly better at cued, than un-cued, than invalidly-cued target locations (Posner, 1980). The same was true even after validity effects came into play (i.e. 50% valid mixed with 50% invalid peripheral cues), with peripheral cues persisting with shifting attention at neutral and invalid conditions (Muller and Rabbitt, 1989). In the case of the latter, the authors report of attention being disengaged from the wrong location which then got redirected towards the actual target location followed by target engagement. This finding is consistent with the view of additional actions prompting delayed response times during invalid trials. However, when the SOA interval surpassed 300 msec, observers responded faster to targets at the un-cued location especially in the invalid trials. In the minds of the observer, this was due to a weaker prospect of a previously attended location being reattended following the withdrawal of attention from that particular region, the term defined as inhibitory after effect or inhibition of return (IoR - Posner & Cohen, 1984). This inhibitory effect had since been actively observed to be a crucial aspect concerned with orienting attention in the direction of new target locations (Klein & MacInnes, 1999) known to facilitate processes such as visual search (Wang & Klein, 2010). Findings from this study of Posner (1980) demonstrated three important stages when shifting attention, i.e. (i) disengagement of attention from attention focus, (ii) orienting attention towards the new target, and (iii) re-engagement with the new target. In addition, with the pre-cue facilitating detection of and response to stimuli presented at the cued location, Posner described attention as a "spotlight that enhances the efficiency of the detection of events within its beam" (Posner, 1980, p. 172).

In fact, studies have also employed the use of such cueing strategies between control individuals and certain patient groups to compare the performance differences across visual fields. For instance, the cued detection studies conducted by Posner et al (1984, 1987) in a group of patients with parietal lobe damage consisted of two potential target locations on either side of a central fixation, with the endogenous cue (arrow) being presented validly (in 80% of the trials) in addition to the invalid and neutral cue (noninformative). A corresponding salient target (box) was presented shortly afterwards either on to the left or right visual field (**figure 12A**). Both the controls and patients with parietal lobe damage were required to respond immediately following target detection. Findings from both groups showed smaller response times for detecting the target (along with higher accuracy) in the valid, but not in the neutral condition, which suggested modulation of attention precisely at the target position in the absence of overt eye movements. In normal participants, the costs and benefits associated with attention shifts was approximately the same regardless of the visual field in which the target appeared (**figure 12B, left panel**). However, in the case of the patient group, the reported findings mentioned response times which were significantly slower when the targets were invalidly pre-cued, compared to both the neutral and valid conditions (**figure 12B, right panel**). That is, the misleading nature of the invalid cue resulted in the shifting of attention to the unattended side of the stimulus display. These findings reflected a problem concerning disengagement of attention (disengagement deficit) from a location that was invalidly pre-cued within the non-neglected right visual field upon presenting the target at the neglected left visual field. This deficit was observed in patient populations with both enduring right hemispheric damage/lesions (Posner et al., 1984), and those with spatial left neglect (Posner et al., 1984; Sieroff, Decaix, Chokron, & Bartolomeo, 2007). All in all, these features suggested impaired exogenous orienting towards targets in opposite-lesional space, a functional deficit in patients with left visual neglect. On the contrary, endogenous orienting was reported to be relatively preserved, if at all slowed, in patients with enduring left unilateral neglect (Bartolomeo, Sieroff, Decaix, & Chokron, 2001). These results further confirmed the close connection between parietal lobes (especially the right parietal lobe) and selective attention.

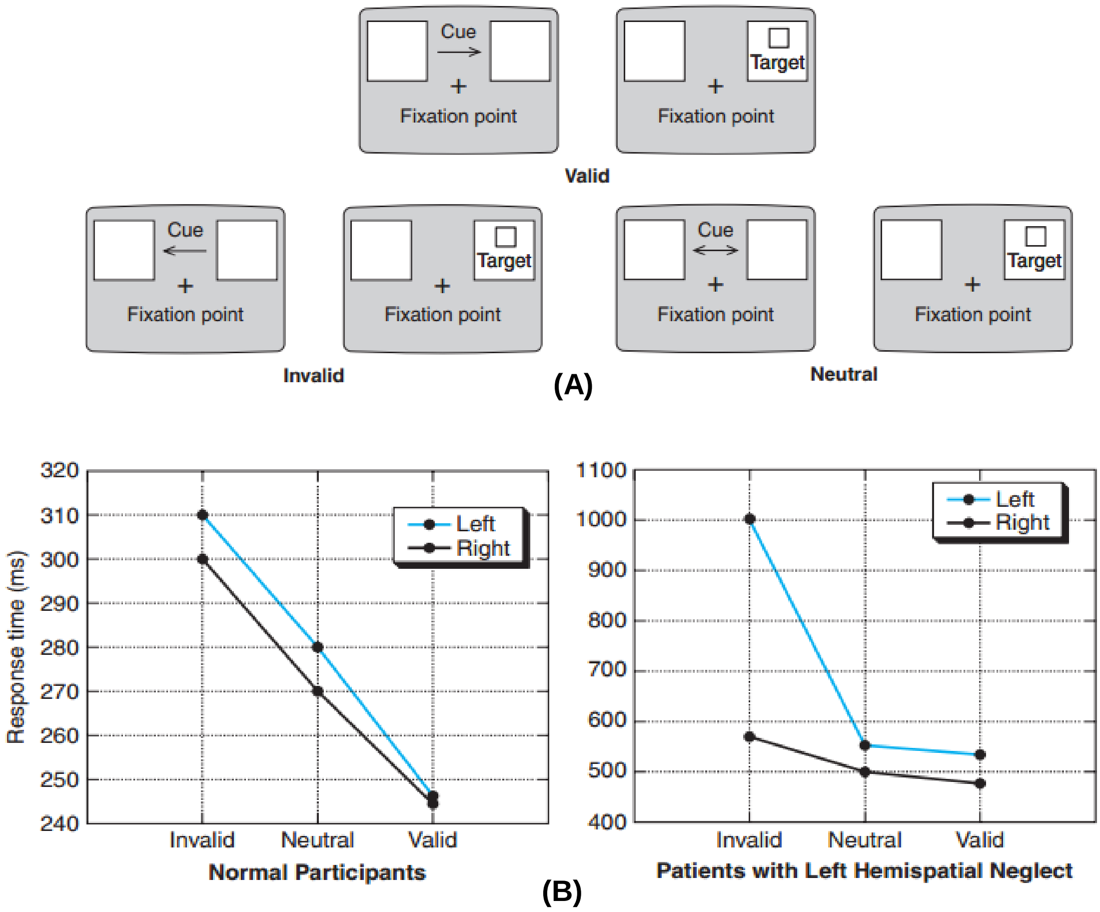

Figure 12: Cuing tasks assessing endogenous and exogenous attention across visual fields. (**a**) Three cueing conditions to which an endogenous cue (arrow) was presented for exogenously positioned target (box) alternating between left and right visual fields. (**b**) Graph showing the difference in response times for both normal and right hemispatial neglect patients. [Source: Adapted from Posner et al (1984, 1987)].

1.6.4.2 Visual Search

Another paradigm used extensively to investigate spatial attention is the visual search paradigm. The term "visual search" refers to the finding for a particular visual target among a background of distractors. A typical visual search task consists of a stimulus screen to which a variable number of distractors (of varying set-size) in addition to a competing target are presented, with reaction time and/or performance accuracy being standard independent measures. In studies of this nature, one key characteristic feature is the search functions and their correlation with set-size as proposed by Treisman's feature integration theory (Treisman, 1988, 2006). According to this theory, perception occurs either in a serial or parallel fashion, both dependent upon the type of search task (i.e. searching a given feature or a conjunction of features). On one hand, for tasks requiring search for a particular target based on a given feature differentiating it from the distractor (e.g. a tilted vs. vertically aligned Gabor patches), perception was said to occur involuntarily without the need for focussed attention (i.e. parallel processing). That is, each stimulus feature (including both target and distractor) matches a given location within a feature map thereby rapidly depicting a target corresponding to a unique feature. On the other hand, tasks requiring search for a particular target based on a conjunction of two or more features was said to occur voluntarily requiring focussed attention so as to rejoin stimulus specific features for recognition of a given stimuli (i.e. serial processing). Based on such a visual search paradigm, salient targets are known to either pop out (thereby grabbing attention instantly and efficiently) or go unnoticed (with significant effort needed on the part of the observer resulting in a limited capacity) during the search process. Hence, as more distractors are presented during a conjunction search, responses tend to be slower and less accurate with the search function typically represented by a steep slope (i.e. inefficient visual search). The opposite is true in feature search where addition of further distractors has no influence on the response times and/or accuracy (i.e. efficient visual search).

One of the classic studies of visual search comes from spatial cueing studies carried out to assess spatial resolution in normal individuals (Yeshurun & Carrasco, 1999). The authors employed three gap detection tasks sets, in addition to vernier resolution, all three of which presented in isolation at varying locations across the search display (1.5 - 6° of eccentricity in the vertical or horizontal axes). An exogenous pre-cue was used in 50% of trials to direct attention automatically to the target location (cue was presented prior to onset of search display), whilst in the rest 50% of the trials the search displays were cued neutrally (uninformative "●"). With participants required to indicate the direction of the gap both rapidly and as accurately, the findings indicated: (i) poor performance at the lowest gap-size, (ii) poor resolution at the largest target eccentricity, and (iii) reduced effect of eccentricity across cued trials in the gap resolution task. More importantly, observers exhibited precise detection of targets appearing at the cued object (which was faster and more accurate) than those appearing when neutrally cued, with similar findings observed in quite a number of other studies (e.g. Carrasco et al., 2000; Huang & Dobkins, 2005; Eckstein, Peterson, Pham, & Droll, 2009). These results indicated that near eccentricity biased the allocation of spatial attention given that the resolution was much stronger at the central regions of the search display. That is, when spatial attention was directed to a pre-cued location, the attention spotlight was free to move at regions far from fixation than compared to the foveal region. The enhancement of spatial resolution by the pre-cue further assisted in the exclusion of noise caused by both the distractors and spatial uncertainty (decisional factor).

A recent study by Fellrath, Blanche-Durbec, Schnider, Jacquemoud, & Ptak (2012) focused on visual search performance between normal participants and patients with left spatial neglect. Participants were subjected to displays consisting of a single target ("**T**") among two types of distractors ("**L**" and "**T**", **figure 13A**) across three different set-sizes (four, eight and sixteen, **figure 13B**). The search array consisted of both target and distractors spanning the left and right visual fields presented at various SOA's, either at preview conditions lasting 300 and 600 msec or simultaneously altogether. The participants were required to respond immediately after target onset, and thereafter withholding response following target offset. Based on the findings observed (**figure 13C**), the patient group demonstrated an inefficient conjunction search with response times increasing concomitantly with increase in set-size, and a visual field asymmetry due to impaired deployment of spatial attention (characteristic of left neglect patients). Although the authors attributed these findings towards biased spatial selection (an effect explained by Desimone & Duncan's (1995) biased competition account of visual search[5]), the findings is better explained by Yeshurun & Carrasco's (1999) findings.

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[5] The biased competition model states that multiple stimuli when presented in a given visual field compete with one another to necessitate the activation of neuron populations, further eliciting competitions against other neurons to bring about enhanced visual attention. The components for this bias mechanism originate from bottom-up (the sensory stimuli available on the stimulus display) and top-down (the goal for an intended task) sources, both of which are crucial for visual search depicted by how well functions relating to both these sources are counterbalanced with respect to each other. For instance, a pop-out effect of a target appearing among background distractors is a perfect example of a bottom-up bias mechanism which aids visual attention to be oriented towards salient locations within a search display. This together with the sudden appearance of a novel stimulus therefore serves to capture attention, so much so the sudden appearance of a novel stimulus helps bias bottom-up attentional orienting. This goes to show that visual search by default is bottom-up dependent with external incoming stimuli serving as an ideal pop-up initiator thereby controlling spatial attention.

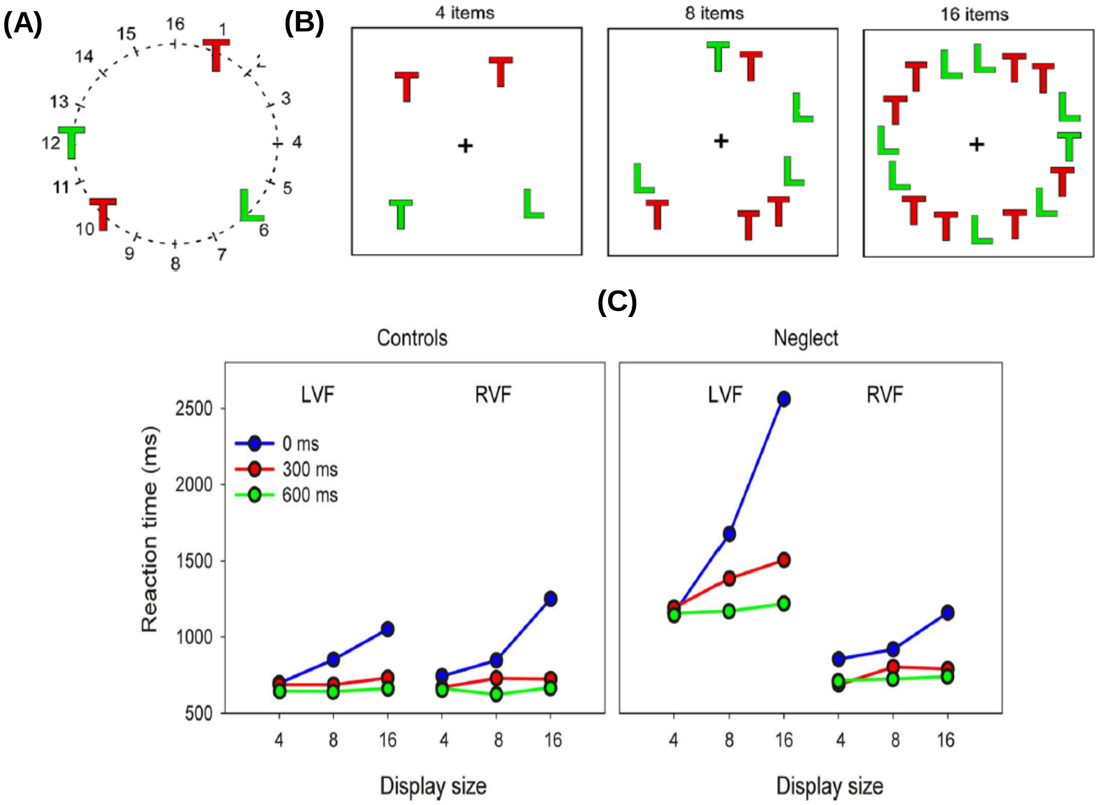

Figure 13: Visual search task assessing discrimination performance across visual fields. (**a**) Circular arrangement of stimuli around fixation, for which (**b**) both a single target and distractors are presented at variable set-sizes. Shape and colour here are characteristic of a conjunction search. (**c**) Line graph showing the difference in response times for both normal and left neglect patients. [Source: Adapted from Fellrath et al (2012)].

Although there were no cues being employed in Fellrath and colleagues study, the neglect patients suffered with increasing set-size on the left as opposed to the right visual field. This can be related to significantly greater noise which left neglect patients find it difficult to exclude. Although the patient group found the conjunction search tasks for both the preview conditions easier, that is because search proceeded from right to left visual field smoothly. Moreover, in conditions taxing reaction time (i.e. at 0 msec), the search process suffered as a result of the sudden stimulus onset which biased the process of attention normalization due to increased decisional uncertainty (given the higher noise present and the late attentional capture from preview conditions). Despite the right parietal lobe deficit in the patient group, these individuals found the instantaneous search task even harder based on items presented on the left visual field to a degree where they were able to accomplish both the preview conditions despite higher reaction times (at the maximum set-size), suggesting a cost-benefit association. This further confirms the important underlying mechanisms which eventually depict optimal attentional selection.

1.6.4.3 Visual crowding

Crowding is yet another complex paradigm extensively studied using visual search. In an alphabetical setting, the letters in a word are positioned in a specified structured sequence. The perception of a given letter in a word therefore becomes difficult to read when the surrounding letters are positioned close together (i.e. "crowding" or "lateral masking"). Visual crowding refers to the deficit in recognizing salient targets in the presence of neighbouring distractors, as first proposed by Korte (1923). Importantly, a minor increase of interletter spacing as in "P A N I C" (compared to the default "PANIC"), may reduce the detrimental effects of crowding without affecting the wholeness of the entire word (i.e. still for all, "PANIC" is perceived as a single entity). Furthermore, a small increase of interletter spacing may not just reduce the effect of crowding, for it also aids in the process of letter position coding which is thought to be very important when it comes to distinguishing between words like "BEAR" and "BARE". Recent theories in relation to processing orthography have assumed the presence of some level of "position uncertainty" based on a letter’s position within a word (Chung & Legge, 2009; Davis, 2010). Thus, increasing the spacing among letters within a word can reduce a letter’s spatial uncertainty and have a beneficial impact on lexical access.

Recent studies elucidate the negative impacts associated with crowding on visual discrimination with the help of different visual tasks such as letter discrimination (Marialuisa, Gloria, Donatella, & Pierluigi, 2009), face discrimination (Faraz, Susan, & David, 2009), orientation averaging (Dakin, Bex, Cass, & Watt, 2009) and motion perception (Maus, Jason, & David, 2010). Bouma (1970, 1973) defined crowding based on the critical spacing of objects, which according to Bouma’s rule is roughly half of the viewing eccentricity. An increase in the number of distractors in the vicinity (i.e. as critical distance between stimuli reduces) independent of its physical dimensions, leads to poor recognition of the target. Its effects are most specific to certain features (shape, size, orientation, contrast and hue) with a corresponding larger effect when the physical features of both the target and distractor are alike, for instance in an orientation discrimination task (Greenwood, Bex, & Dakin, 2010). In this context, crowding is defined as an elevation of target tilt threshold as a result of distractors (perfectly vertical) that occurs even when there is no uncertainty regarding which objects are tilted (target) and which are not.

A range of mechanisms fundamental to the current understanding of crowding theories have been proposed in the past (for a review see Levi, 2008). However, two accounts require special mention, namely the attentional and feature integration accounts.

According to the attentional account, the process of accurate interpretation is regarded to be highly important when detecting and discriminating the identity of a particular object, an attentional function required for accurate encoding of position and tracking of location over time for mobile stimuli (Cavanagh & Alvarez, 2005). This functioning capability is said to be restricted due to poor attentional resolution resulting in crowding (Intriligator & Cavanagh, 2001). With crowding being modulated by spatial attention, detection becomes smoother when target positions occupy both the left and right visual fields with each visual field having its independent attentional resources, i.e. a bilateral field advantage (Chakravarthi & Cavanagh, 2009). Moreover, the crowding effect is highly dependent on both the target-distractor spacing and stimulus set-size (Franconeri, Jonathan, & Scimeca, 2010). A second account is that of feature integration. The pathway towards successful object perception follows a two-stage process, the initial stage where a stimulus gets identified so as to extract the stimulus features (i.e. image components which are different from others, Pelli, Burns, Farell, & Moore-Page, 2006). The second stage involves integrating the previously isolated stimulus features. Therefore, crowding is also speculated to be a result of inappropriate matching of the second stage filter (template) to the corresponding target (Levi, Klein, & Carney, 2000), with such effects impairing identification and not object detection (Whitney & Levi, 2011).

It has been established that there are several diagnostic criterion for crowding and most authors prefer to use these as converging evidence to help characterize and distinguish crowding from other effects such as masking (Pelli et al., 2004). A study into crowding effect using a de-masking paradigm (i.e. the information that is masked is not passively filtered in early processing but can be retrieved: Geiger & Lettvin, 1987) in letter string identification has also yielded consistent findings. In this stimulus presentation, the letter string gradually emerged from the perceptual mask with inter-stimuli spacing manipulated to varying lengths. The stimuli that appeared at any one time were either familiar words or pronounceable nonwords. The findings from this study showed that decreasing the distance between letters impaired nonword more than word identification, thus implying a top-down modulation of the crowding effect. Stimulus features was identified as a further determinant of crowding, with interference assumed to occur only when distractors share the characteristic dimension of the target such as colour (Kooi, Toet, Tripathy, & Levi, 1994) or orientation (Bernard & Chung, 2011). When control participants were asked to identify the tilted Gabor patches, Bernard & Chung (2011) found that accuracy decreased with increasing set-size, even with spacing held constant. Using orientation identification of rotated Ts, Parkes, Lund, Angelucci, Solomon, & Morgan (2001) found that thresholds in normal adults fell linearly as the number of target locations increased from 1 to 9.

A study by Freeman & Pelli (2007) investigated the role of attention in crowding using a cued change blindness paradigm in normal individuals. In such a paradigm, the observer was presented with an image and following a brief time lag, sees another altered form of the first image. They measured capacity to identify change detection (i.e. to infer if the capacity of the observers' awareness was limited by selective attention or not) for widely and narrowly spaced letters during the presence and absence of exogenously presented valid cues (pre and post-cue). Pre-cuing enabled the observer to deploy attention to the target location, whilst post-cueing enabled reduction of the location uncertainty in the decision process. Thus, the authors attributed any potential benefit between pre-cues, compared to post-cues, to equate for attentional modulation for target detection. The results illustrated reduced target identification by a factor of 1.5 or more in all four spacing manipulations no matter the type of cue used, with a corresponding 40% reduction in widely spaced letters when being post-cued alone (**figure 14**). Two important outcomes of this study were apparent. First, reduced spacing and further addition of distractors did not impair overall cued change detection (unlike when un-cued). Secondly, the impact of individual cues on crowding revealed that pre-cueing in general tended to relieve the effects of crowding. That is, deploying spatial attention to the target location via attentional pre-cues served to reduce the detrimental crowding effect.

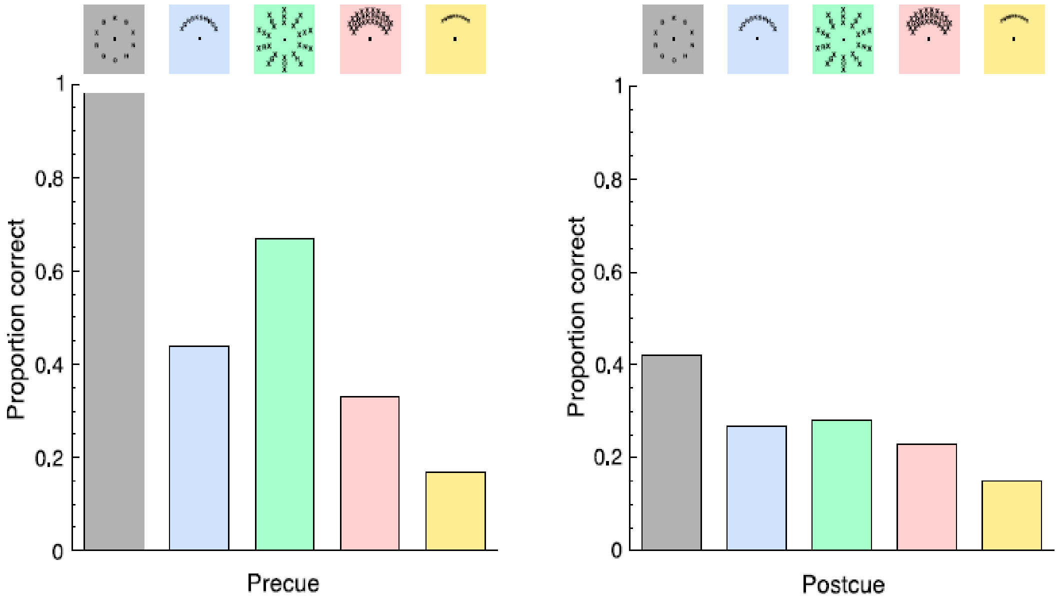

Figure 14: Letter identification across pre and post-cued crowded displays. The letter spacing's used in this study varied from wide spacing (3.7°) – gray; narrow spacing (1.1°) – blue; wide spacing with two 'X' distractors on either side – green; narrow spacing with distractors (1.1°) – pink; and extra narrow spacing (0.63°) - yellow. No matter when cued, all levels of spacing (except pre-cued widely spaced) impair letter identification. [Source: Adapted from Freeman and Pelli (2007)].

Given the finding of a detrimental set-size effect common to most of the above mentioned studies, the crowding deficit has been characterized by elevated degree of location uncertainty (i.e. loss of positional information). For instance, a study measuring contrast sensitivity in normal adults reported that observers regularly confound the target with surrounding distractors (Strasburger, 2005). In addition, Popple & Levi (2005) in their study with amblyopic patients reported that observers were able to spot a maximum of six spreaded stimuli in the correct sequence, unlike that with crowded stimuli where only a maximum of four stimuli was detected. In both studies, the fraction of uncertainty concerning stimulus positions in the crowded displays was on the higher side than expected at a probability level. This was possibly influenced by some form of noise mismanagement. Further to this, Nandy & Tjan (2007) using a classification image study demonstrated a significant association between the error counts and target-distractor feature detection thresholds (i.e. for one half of the distractor sharing a common target feature) when presented in the periphery, unlike at the foveal region. The authors offered their support towards source confusion as the basis of crowding. This pattern of crowding goes to show that processes required for target recognition may improperly integrate some features of the distractors unlike those concerned with target detection. This takes us back to the point of attention as an important filter (template) mechanism, thereby excluding "noise" spilling in from nearby distractors at the target region. The next section shall briefly look at some of these mechanisms.

1.6.5 Mechanisms of Attention

The term "attention" is commonly used in verbal communication on a day to day basis so as to draw observation towards a given action. However, in the case of psychology, little has it managed to express when it comes to defining its precise meaning in an experimental setting. The reason being, many a time investigators prefer using the term attention when referring to particular action(s), rather than signifying the processes which actually backs up attention in a cognitive sense. That is, by attributing attention to conducting a particular experimental task, by no means does it comprehensively explain the complex selection processes and mechanisms which govern the successful fulfilment of that particular task. For instance, a study participant is given a task involving two Gabor patches presented peripherally on either side of central fixation (one which is oriented to the right - 45°, and one which is perfectly vertical - 0°) with the participant requiring to respond immediately upon detecting the tilted target. In a task such as this, even though the task involves the participant in drawing attention towards the tilted Gabor patch, actually little is known about what sort of mechanisms such an attention task would entail. Based on what was observed with the naked eye, it is obvious that tasks such as these would not explain whether or not attended Gabor patch was "enhanced" compared to the unattended Gabor patches. Same applies when it comes to knowing if the unattended Gabor patches were "inhibited" compared to the attended Gabor patch, or even both. Before we proceed any further, my next aim is to introduce the key components of visual search. I begin by introducing a short summary of computation modelling frameworks, to help set the theme for the rest of the research studies to follow.

Unlike both the feature integration theory (FIT) and signal detection theory (SDT)[6] accounts, the perceptual template model (PTM) goes a step further by enabling theorists to study visual search in great detail (Dosher & Lu, 1997). The PTM explain the means by which attention manipulates the overall negative influence of external noise when added to a fully functioning search system (see **figure 15**, regions of interest highlighted in green). In this way, it gives a measure based on the extent of modulation required for target-distractor discrimination. The initial step towards successful perception of an incoming visual stimulus is to identify its basic features (Pelli et al., 2006). The incoming stimulus information must first undergo analysis by virtue of a perceptual template. In an attempt to improve overall task performance, attentional functions ensure smooth interaction with the template and this happens via three mechanisms, namely stimulus enhancement, external noise exclusion, and internal (multiplicative and additive) noise reduction. Signal enhancement is a mathematical function in terms of PTM which serves to reduce internal noise, thereby improving performance in the presence of low external noise. External noise exclusion functions by curtailing the influence of distractor noise via appropriate means of filtering excess external noise which the system cannot handle. This is achieved by actively narrowing/focusing the template over relevant spatial areas belonging to the external stimulus. Internal noise exclusion functions similar to that of signal enhancement, just that it is highly sensitive to varying external noise (e.g. set-size).

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[6] Of recent times, investigators have begun looking at attentional functions in terms of human psychological thresholds. Two prominent modelling studies which received appraisal over the years were the FIT and SDT. Increased visual search times were previously attributed to FIT where search performance was known to result from a two-stage visual process (Treisman & Gelade, 1980). The first being a pre-attentive stage (prior to the deployment of attention) comprising of spatial feature maps (e.g. orientation) to which corresponding neurons act selectively based on a restricted range of values. As a result, items operate in parallel allowing instantaneous processing yielding search times independent of set-size. Failure in target isolation leads to the second limited-capacity serial stage, whereby attention focuses either at single or grouped items (serially in succession), resulting in increased search times proportional to the set-size. However, in the case of SDT, both detection and discrimination are considered in terms of unlimited-capacity (parallel processing) and a decision component (compared to FIT’s unlimited-capacity (parallel) plus limited-capacity-attention mediated components) so as to calculate both set-size and the attentional effects of distractor (noise) exclusion on search performance (Bradley et al., 1987).

That is, with increasing set-size the internal noise also increases. As long as internal noise remains at lower levels, task performance is at its optimum (Carrasco, 2011).

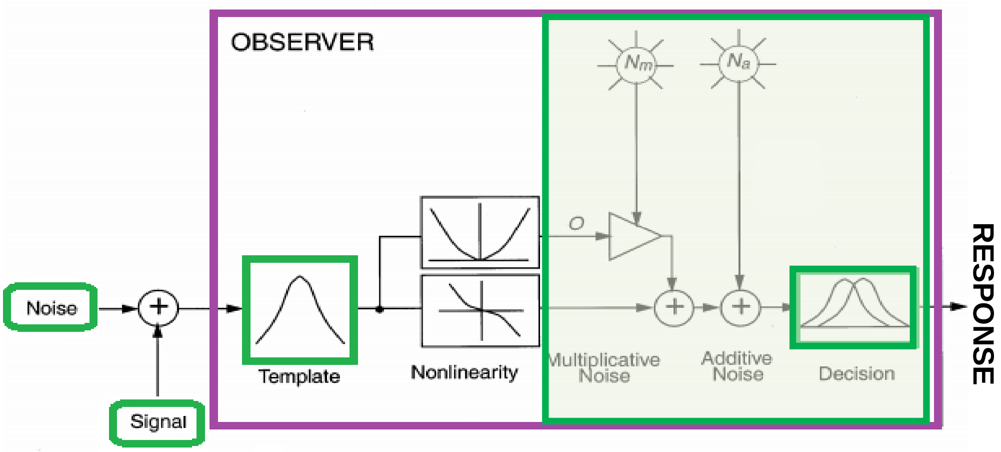

Figure 15: Schematic representation of the perceptual template model. Areas highlighted within the green box represent: (**i**) incoming visual signal (e.g. a search screen) containing some form of external noise (e.g. presence of distractors), (**ii**) the stimulus features which then pass through a template extracting relevant stimulus features. (**iii**) The internal additive and multiplicative noise (e.g. sampling noise, coarse coding of stimulus features, information loss during transfer) increases proportionally with the noise existing with the signal (signal plus external noise), (**iv**) all of which influences the weight of the internal decision process, which eventually characterises task performance. [Source: Adapted from Dosher & Lu (1999)].

Central to the understanding of tasks such as visual search are two main mechanisms (signal enhancement and noise exclusion) known to explain attentional functions and their influence on visual perception. Therefore, by manipulating attention using cueing strategies, one is actually capable of exploiting a given attentional function. According to Nakayama & Mackeben (1989), transient attention is believed to operate at an early stage of visual processing where pre-cueing attention enabled efficient filtering of noise influencing target discriminability. The stimuli present within the search display are individually examined despite the information contained within them are naturally noisy (due to the presence of distractors). When these stimuli were pre-cued at the target location, corresponding increase in the signal-to-noise ratio ensures that the information to perceive at the cued location was of higher quality, the mechanism referred to as signal enhancement (i.e. increased sensory representation, Liu et al., 2009). Laboratory findings further backed this up, where Lu & Dosher (2000) and Dosher & Lu (2000a) found stimulus enhancement when the search display was pre-cued, with performance varying across a range of external noise levels. They found that at high noise levels, attention enhanced the signal and reduced the effect of external (distractors) and internal noise (spatial uncertainty), unlike at low noise levels which was predominantly optimum signal enhancement. Same was true with studies assessing contrast sensitivity functions where an increase in contrast sensitivity occurred as a result of signal enhancement in the absence of distractors. This is based on the finding as witnessed in the study carried out by Posner, Nissen, & Ogden (1978) where attention in noiseless conditions equalled optimum performance (**figure 16**). Further support of this attention modulation came from studies assessing spatial resolution with participants required to detect a texture target amidst a background containing orthogonal tilts. Their suggestion meant that the smaller the area in which processing took place, greater the enhancement of spatial resolution (e.g. Carrasco, Williams, & Yeshurun, 2002; Yeshurun & Carrasco, 1998; Yeshurun, Montagna, & Carrasco, 2008).

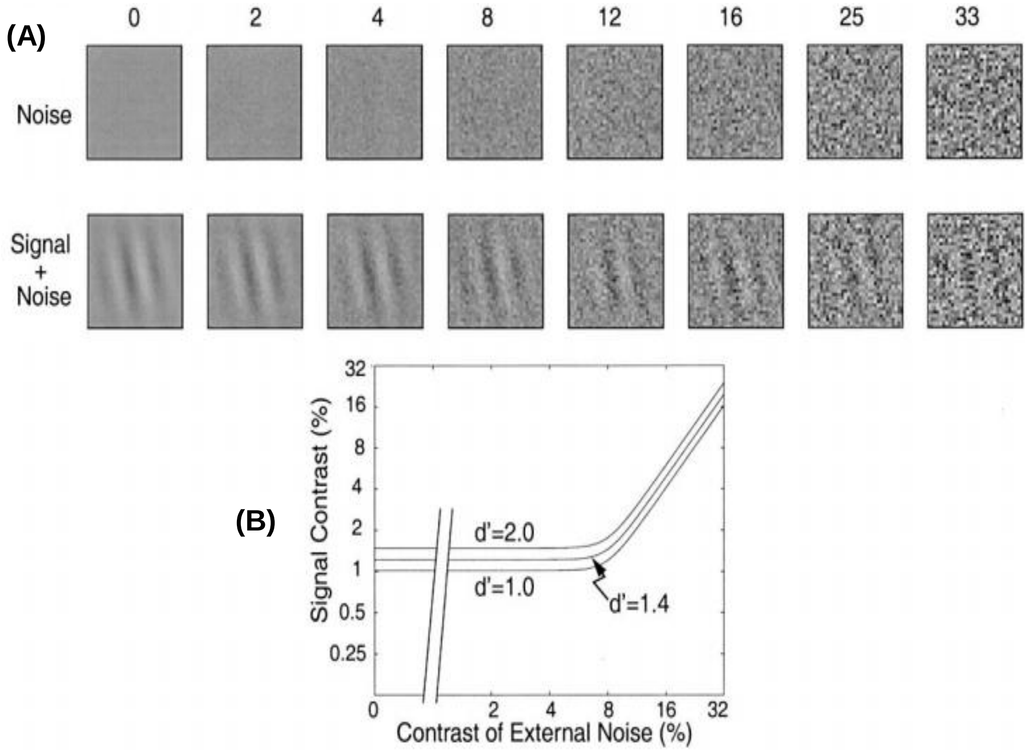

Figure 16: Stimulus detection and discrimination in noise variant environments. (**a**) The input signal (an oriented Gabor patch) consisting of various levels of external noise (white noise) when presented impacted on task performance (signal contrast in relation to detection and discrimination accuracy). (**b**) Graph showing contrast thresholds as a function of external noise, with flat regions denoting low external noise, with an increase associated at regions of higher external noise. Performance in the flat region of external noise equates internal noise levels, so as long as the external noise remains low, decisional factors remain unaffected. The opposite is true at higher external noise weighing down decision, which then results in poor task performance. [Source: Adapted from Dosher & Lu (1999)].

In summary…

The aforementioned sections looked at the types of attention including some of the early and late theories governing its selective function in visual perception. The sections focused on a handful of studies and their paradigms (cueing, search and crowding) as previously mentioned in the literature (conducted within control and certain patient populations). However, not many studies have attempted to explain the underlying attentional mechanisms. Two main attention mechanisms were identified, i.e. signal enhancement and noise exclusion. We believe both these mechanisms play a significant part in some, if not all, of the visual deficits common to individuals with dyslexia. We now shift our interest towards (visual) deficits in dyslexia based on the aforementioned classical attention studies and their mechanisms.

1.6.6 Attention Deficits in Dyslexia

Recent research endeavoured in various neuropsychology disciplines concerning the causes of dyslexia have thus far demonstrated various laboratory findings related to RAN dysfunction (Pan & Shu, 2014); temporal auditory processing deficits (Raschle, Sterling, Meissner, & Gaab, 2013); abnormal cortical asymmetry (Dole, Meunier, & Hoen, 2013); cerebellar deficit (Yang, Bi, Long, & Tao, 2013); and magnocellular deficits (Yamamoto et al., 2013). However, the main cause underlying dyslexia has been the subject of much debate. A favourable account is that of phonological deficit which postulates that individuals with dyslexia have a specific impairment in representing, storing and/or recalling speech sounds. Support for phonological theory comes from research evidence showing that persons with dyslexia perform poorly for instance on tasks requiring phonemic awareness, phonological learning and non-word repetition (Fernandes, Vale, Martins, Morais, & Kolinsky, 2013). However, in the recent past a large growing body of research have begun focusing on non-linguistic aspects such as visual attention, to be the basis in which reading difficulties manifest in dyslexia. Reading is a visually challenging process which requires precision when it comes to processing incoming textual information. Therefore, the role of attention ensures selection of an appropriate region of the text for further processing, studied in the current era with close relevance to the attention spotlight theory (Posner, 1980). According to this theory, when attention is illuminated at visual fields within the spotlight (letter string), a significant reduction of search time enables the target feature to be detected faster. This causes a significant lowering of the threshold to a level which makes individual stimuli features easily distinguishable from the rest. In neurological terms, the enhancement brought about by deploying more neurones at a given visual field, enhances the processing of an attended target. This means the attentional load entirely depends on the capacity to process more than one object, as a result it is a critical attribute which controls the size of the spotlight (Bellgrove, Eramudugolla, Newman, Vance, & Mattingley, 2013). In the regions outside this spotlight, the exact opposite is true with elevated search time with partial filtration of visual information and increased thresholds for non-attended stimuli. Several studies performed with individuals with dyslexia have gone on to report a number of attention related deficits.

1.6.6.1 Attention Blink

The attentional blink (AB) paradigm concerned with the rapid serial visual presentation (RSVP) of stimuli, evolved from one of the very first studies carried out by Broadbent & Broadbent (1987) requiring control individuals to identify and report the sequence of a pair of target stimuli when presented between a temporal time lag (T1 and T2). The choice of stimuli for both parts varied along some physical characteristic (such as digit) presented within a stream of stimuli (often alphanumeric characters). This time frame was varied at various intervals in an attempt to examine the distractor interference as a function of time. Participants were reported to be impaired at detecting the T2 component compared to T1, especially when T2 happened to be presented within 500 msec following the correct identification of T1 (Raymond, Shapiro, & Arnell, 1992; Ward, Duncan, & Shapiro, 1996). The first part of Raymond and colleagues study involved ignoring T1 (variable coloured target) whilst reporting just T2. The participants showed no difficulties which suggested that the observed effect was due to an attentional effect rather than a sensory/masking effect. In the second part of their study, the screen immediately after T1 (probe) was replaced with a distractor/mask. On this occasion, the participants found it difficult to detect T2 given the interference but the effect was withdrawn once the probe was replaced with a blank interval. Raymond and colleagues named this as an AB deficit, an effect which is comparable to the suppressive nature of visual processing known to arise while performing rapid saccadic eye movements. Thus, the AB deficit clearly explained constraints in the rate of visual processing, an effect solely attributed to two factors. Firstly, studies have shown that a complex task such as AB demands a lot of attentional resources to carry out both selection and identification. Moreover, the background distractors also end up being identified and represented within the short-term memory, which clearly signifies limited capacity (Akyurek, Hommel, & Joliceur, 2007). Secondly, the short delay between T1 and T2 is thought to influence detection and selection of the target. For instance, the stimuli when presented in the order T2 followed by T1, T2 undergoes processing gaining access into short-term memory, which is therein subjected to passive decay thereby producing an interference effect. Suppose, the next sequence of presentation follows the order T1, T2 with a slightly extended interstimulus duration, the increased time lag allows T1 to be fully processed and represented, thereby sparing sufficient attentional resources for the selection and processing of T2 (Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005).

There have been many studies examining AB within the dyslexic population (Buchholz & Aimola Davies, 2007; Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; Hari et al., 1999; Lacroix et al., 2005; Lallier Lallier, Donnadieu, Berger, & Valdois’s, 2009; Lallier, Donnadieu, & Valdois, 2010; Visser, Boden, & Giaschi, 2004). The study carried out by Hari & colleagues (1999) investigated AB in AwDys using a RSVP task consisting of a random letter in white font (T1), "X" in black font (T2) and the remaining letters in black font (distractors), with participants required to identify and respond whether T2 was similar to that of T1. Findings from this study demonstrated a higher SOA in AwDys with optimum performance reported to be at 700 msec, compared to the controls (540 msec). Based on this prolonged AB in the dyslexic group, the authors suggested that the limit capacity (short-term memory) extended over time longer than it did with the control group - a deficit which they proposed "prolonged attention dwell time". But these findings were open to criticism given that letter naming have previously been shown to be poorer with dyslexics (e.g. Landerl, 2001), so ideally this deficit could have also been due to the difficulty in handling letters rather than it being purely attentional.

This was soon followed by the study of Visser et al (2004) who investigated the extent of interference effect caused by T1 on T2 identification carried out in a group of CwDys. The findings reported from this study showed no group differences, thereby concluding the fact that T2 interference was not the only factor giving rise to the AB deficit, but it was also related to a deficit in identifying the T1 to start with. This was in line with the idea of a limited capacity, i.e. having attended to T1 and given the short space of time, sufficient resources is thought to have not been freed up, the reason why it could have resulted in the "confusion" of T1 with the distractors which soon followed (Raymond et al., 1992). In particular, the prolonged AB deficit was found to occur only when the distractors were totally different from the targets (T1), further suggesting that the AB deficit in dyslexia could be a result of poor allocation of attentional resources crucial for target identification. Interestingly, Visser et al (2004) came up with a further observation whereby the AB-SOA was brief in duration compared to that found by Hari et al (1999), the former suggesting that if at all, the AB deficits observed in that of Hari et al (1999) to be a result of an attentional difficulty, which to some degree could have cropped up due to developmental delays. That is, the attentional system is regarded to be somewhat "sluggish" when considering the rate of development in some CwDys, while it can also be completely un-matured upon reaching adulthood. In an attempt to find out whether dyslexic adolescents needed additional resource allowances when shifting their attention, Lacroix & colleagues (2005) found a far lower SOA in the dyslexic group compared to the control group. The reported findings were totally different to that reported previously by Hari et al (1999) and Visser et al (2004). Lacroix and colleagues related their findings of an AB deficit in dyslexia to a difficulty in automatic processing of the stimuli (digits), a process which occurs ahead of preliminary encoding function, implying an inability to recall at the back end of each trial. Nevertheless, T1 accuracy was similar in both groups suggesting that dyslexics, just like the controls, were capable at assigning relevant resources to retain the targets within the working memory.

In another study conducted by Buchholz & Aimola Davies (2007), the authors employed two different sets of targets (letter and digit in red font) tested separately (in two tasks) among common distractors (black digits). The findings indicated a general difficulty with every AwDys when processing briskly presented digit stimuli, thereby conforming to findings made by Hari et al (1999) and Visser et al (2004). The two most recent studies by Lallier & colleagues (2009, 2010) also offered evidence of prolonged AB/dwell time in dyslexia using a different methodology altogether. The authors employed a curve fitting method to quantify the AB deficit with specific parameters such as AB duration (dwell time), AB minimum (worse performance for T2 detection), and AB amplitude (difference between the worse and best T2 detection). In Lallier et al (2009) study consisting of AwDys and matched controls, it was demonstrated that the former had a longer AB along with higher AB amplitude unlike in the control group. Similarly, in the follow-up study by Lallier et al (2010) carried out in CwDys unmatched to a control group, the investigators opted to use a single and dual task controlling for task sensitivity in order to evaluate the capacity to shift attention in a temporal fashion. It was reported that CwDys, like controls, had similar dwell time, a finding which was contrary to that of Facoetti et al (2008). However, the dyslexic group exhibited a lower AB minimum unlike controls. The authors highlighted the importance when considering AB deficits in light of reading related difficulties, since a given pathology involving attentional functions may sometimes fail to develop in an optimal way. However, there was some level of criticism shed by McLean, Castles, Coltheart, & Stuart (2010) claiming that the aforementioned findings were related to weaker performance in dual-targets rather than a specific attentional blink deficit. McLean and colleagues made this claim based on a lack of profound attentional blink deficits in CwDys. That is, although previous studies have demonstrated a difference in the lag when considering main group effects, they claimed that these studies failed to demonstrate group by lag interactions for T2 detection accuracy in the dual target condition. For instance, although Lacroix et al (2005) found a significant group by lag interaction in their sample of dyslexic adolescence, these participants was reported to have a much better task performance compared to the control group. In the case of Lallier et al (2010), a significant main effect of group, a group by lag interaction, in addition to poorer attentional blink was reported within a very small group of CwDys. The latter can be equally criticised based on the smaller sample of dyslexics which could have biased the interpretation of the results somewhat.

Nevertheless, a follow-up study by Laasonen et al (2012) demonstrated prolonged blink in AwDys (unlike with the adult ADHD group) when the AB task required processing two targets. Facoetti et al (2008) reported findings in CwDys demonstrating difficulties when performing AB tasks, a finding similar to Laasonen and colleagues. Findings based on Facoetti and colleagues study confirmed an AB deficit similar to that proposed previously (Hari et al., 1999; Buchholz & Aimola Davies, 2007). In their earliest study, the use of AB task helped them to deduce potential deficits in shifting attention. In particular, they were keen to know whether dyslexic individuals were able to engage and disengage their non-spatial attention. They measured both attention masking, AM (impairment at identifying T1 - concerned with attention engagement) and AB (impairment at identifying T2 - concerned with attention disengagement) when rapidly presented with alternating T1 (consisting of various letter stimuli) and T2 (consisting of distractors "8"). Findings from this study demonstrated a deficit concerned with both AB (54%) and AM (77%). Furthermore, AB and AM correlated strongly with nonword reading measure (very similar to Badcock et al., 2008; Lallier et al., 2010; McLean et al., 2010), where Facoetti and colleagues concluded that these attention-specific difficulties (attention engagement and disengagement) "mimic a primary signal processing deficit because the inefficient attentional window will expose object perception to major interference from near temporal as well as spatial noisy distractors (i.e. multi-sensory perceptual noise exclusion impairment caused by attentional selection deficit)" (Facoetti et al., 2008, p. 1230).

1.6.6.2 Visual Crowding

Visual crowding has generally been regarded as a poor ability to discriminate a visual target when present in the close vicinity of surrounding distractors. Crowding effects have been predominantly reported using letter and letter-like visual stimuli with both C&AwDys

(Hawelka & Wimmer, 2005, Martelli, Filippo, Spinelli, & Zoccolotti, 2009; Vidyasagar & Pammer, 1999). The very first of these studies conducted by Bouma & Legein (1977) utilized letter triplets presented at various eccentricities to CwDys. It was found that these children were extremely hampered at letter identification (when they were presented in closer proximity to each other) in the presence of flankers at the periphery unlike when letters were presented in isolation. Bouma related these preliminary findings of his to potential deficits associated with attention allocation and/or abnormally elevated level of lateral inhibition. Thereafter, a study by Atkinson (1991, 1993) measuring visual acuity for letter stimuli presented at foveal vision, either in isolation (using letters "C" and "O") or whilst surrounded by other letters (using Cambridge crowding cards), found severe crowding effects in CwDys compared to age and reading level matched controls. Flom (1991) argued that despite selective attention, increased crowding effect at the foveal region may be linked to contour interaction. A follow-up study by Leat, Li, & Epp (1999) proved it to be the case demonstrating a greater crowding effect at the periphery compared to that at the fovea, where the authors also mention the cause relating it to contour interaction in addition to attentional factors. To make matters even more interesting, one study, in an attempt to show a link between subliminal attention modulation and enhanced orientation selective adaptation in a crowded setting (beyond the limit of the spatial resolution of attention), had authors suggesting that crowding was in fact a detrimental reading related effect resulting from a processing deficit known to crop up sometime during attentional selection, a suggestion which meant early sensory processing were pretty much intact (Montaser & Rajimehr, 2005).

Studies investigating the crowding phenomenon have also looked at its effects in other languages producing mixed findings. For instance, Spinelli, Luca, Judica, & Zoccolotti (2002) studied the effects of crowding between a group of Italian and English speaking children carried out using two separate identification tasks. The first study utilized word/symbol-strings, whereby the children were required to identify these when presented in isolation or in the presence of other surrounding words/symbol-strings. The findings revealed slower identification of both words and symbol-strings in a dyslexic subgroup compared to the controls (that too despite little evidence of phonological problems present in Italian children), which prompted the authors to conclude that the crowding effects came into play well before linguistic analysis. The second study involved the manipulation of inter-letter spacing, and much to the surprise of the authors a minority of CwDys were reported to overcome crowding at larger inter-letter spacing. These findings prompted Spinelli and colleagues to argue that the crowding effect was not significantly influenced by attentional or linguistic factors based on their experimental conditions. In light of these findings, the authors did not evaluate the critical spacing separating the letters[7], in addition to a more indirect approach when assessing the relationship between crowding and reading rate. Furthermore, it was demonstrated that the critical print-sizes were significantly larger compared to controls (O'Brien et al., 2005), where the dyslexics required a larger print to achieve reading fluency. One criticism fuelled against this finding is that the authors did not tie it well with crowding nor was it attributed to alternative forms of reasoning. Nevertheless, O'Brien and colleagues claimed that different theoretical proposals had the tendency to elucidate an array of findings, specifying the need for future studies to make further inroads.

It was the study of Martelli et al (2009) which added some stability to the crowding literature in dyslexia linking it with the characteristic letter string processing deficit. They measured contrast thresholds for identifying letters and words as a function of stimulus duration between CwDys and control children. On one hand, when stimulus displays were presented for a brief duration (200 msec), thresholds were higher in CwDys than normally reading children for words but not for letters, confirming a letter string processing deficit. On the other hand, when stimulus displays were presented for a longer duration (2000 msec), word thresholds were comparable in both the groups, suggesting that perceptual distractor exclusion could depend on "sluggish sampling" of letters in a crowded condition. More importantly, the authors measured the spacing between target letters and two distractors as a function of eccentricity. In order to identify a letter in the peripheral visual field at the same criterion level as controls, CwDys needed larger spacing (a factor of about 1.5) between the target letter and the distractors. This goes to show that the critical spacing was larger in CwDys at all eccentricities tested with a larger proportionality (0.95) compared to controls (0.62). Martelli and colleagues concluded that the string processing was sluggish in individuals with dyslexia because of greater crowding which seemed to limit the letter identification in displays containing arrays of letter elements across peripheral extremities.

A handful of studies have also attempted to study the crowding effect on response times in an identification task consisting of words, pseudo-words, nonwords and symbol strings across different languages (Bellocchi & Bastien, 2007; Bellocchi, Bastien-Toniazzo, &

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[7] In response to the critical spacing (i.e. the distance separating the target from the fixation point when presented peripherally), Felisberti et al (2005) contradicts the idea of crowding being very dependent on target-distractor separation. In their study, there was no evidence of crowding in the majority of their control sample when both the target and distractors were positioned on different planes. If it all, the target-distractor distance influence the conspicuousness of a target in relation to the surrounding distractor(s) when positioned close together (e.g. Kooi et al., 1994). That is, they were considered to be perceptually similar thereby diminishing the pop-out effect and associative preattentive processing (Treisman, 1980).

Ducrot, 2013). Upon comparing both French and Italian CwDys to normal readers, findings revealed slower identification (approximately 100 msec) of a central target when surrounded by distractors (a finding identical to that of Spinelli et al., 2002). Interestingly, when the dyslexic data was pooled separately on an individual basis, the authors reported of two dyslexic subgroups, with crowding affecting nonword and symbol-string identification in "moderate dyslexics" compared to "severe dyslexics". Additionally, the former subgroup when compared to the control readers demonstrated a crowding effect in nonword identification. The authors interpreted their findings in relation to a parafoveal advantage, a common characteristic of dyslexia (e.g. Geiger, Lettvin, & Zegarra, 1992). Importantly, the authors mentioned the importance of considering the stimulus types and strategies employed in studies which could influence the reading fluency ascribed to dyslexic individuals of varying lengths of severity. Further to this, Callens, Whitney, Tops, & Brysbaert (2013) recently reported that the level of crowding experienced by a group of dyslexic students (compared to the control group) correlated significantly with word reading abilities. This goes to show that lateral inhibition among letters may be the predicting factor for better word reading performance in dyslexics similar to that found in both the language types of Bellocchi and colleagues.

Interestingly and yet so strangely, the study by Shovman & Ahissar (2006) have criticised the link between attention and crowding effect in dyslexia claiming it to be rather "impure". The authors used a single word reading task in its normal sense (after having excluded the phonological, morphological, semantic, etc components) manipulating components such as letter-size, interletter spacing, and visual noise in an attempt to investigate the direct visual contributions to reading deficits. The type of stimuli used was Georgian letters to which both the control and dyslexic university attending adults were unfamiliar. The two factors key to this criticism is the spacing (crowding single words) and contrast sensitivity (letter identification when presented either on a uniform gray background or embedded in white noise). Findings based on the overall performance of the dyslexic group indicated neither a crowding nor a noise deficit similar to that observed in matched controls. The authors suggested that visual aspects do not limit the dyslexics reading performance, where they further stated, "… it thus seems more likely to interpret their troubling visual stress as a consequence rather than a cause of reading difficulties. Dyslexics probably need to acquire more accurate visual information, compared with controls, to compensate for their phonological deficits, perhaps due to impoverished phonological representations. Hence, for dyslexics, the task of reading may put a heavier load on visual attention compared to their peers" (p. 3523, but see Levi, 2008).

However, the study by Crutch & Warrington (2009) provided evidence of a crowding effect further extending the current findings into a neurological medium beyond single letter recognition tasks. The authors tested two patients with posterior cortical atrophy (PCA) possessing dyslexic-like syndromes. PCA is a progressive neurodegenerative condition which entails prominent tissue loss concerned with regions such as the occipital, parietal and posterior temporal cortices, with such patients reported to demonstrate reading difficulties especially with that of word length, the reason why they are also referred by the name attentional dyslexics or neglect dyslexia. The findings from this study showed that both PCA patients demonstrated a significant effect of crowding on target letter identification (increasing target identification accuracy with increasing target–distractor spacing). However, in the presence of a refined distractor (having a reverse contrast polarity as opposed to its earlier form) the crowding effect was significantly reduced. This crowding effect interacted with letter confusability, i.e. with the presence of high-confusability letters being crowded resulted in a difficulty in identification, and vice versa. However, this was case only when patients attempted to identify distractor letter targets, where the confusability effect improved when identifying single un-crowded letter stimuli. The increased letter spacing improved reading accuracy but, in most cases, this improved performance further resulted in the slowness of reading. The author's state that, "increasing spacing improved individual letter identification but damaged whole-word form and/or parallel letter processing. This is consistent with the increase in word-reading speed observed in both central and peripheral vision, an increase ascribed to disruption of word form processing and a decrease in the number of letters captured within the visual span." (p. 493). That is, the loss of information in single letter identification during high letter confusability reflects abnormally low signal-to-noise ratios needed for letter detection (according to Crutch & Warrington, 2009). In such cases, parallel letter processing is prevented because it becomes difficult to distinguish target letters from visually similar distractor items, since the impoverished visual attention span does not have the sufficiency to distribute attention over an entire word.

Of recent times studies have begun looking at even varying the physical properties of stimuli to gain a better appreciation of the crowding effect in dyslexia. Studies have demonstrated improved reading rates when the reading material concerned was tailored to meet the requirements of individual dyslexic individuals, achieved via testing the flexibility of interletter/word spacing. For instance, Zorzi et al (2012) demonstrated the benefits which increased letter spacing had on the reading rates of Italian and French CwDys who in actual fact suffered to a great deal when the search array was crowded. Same was true based on the findings of Perea, Panadero, Moret-Tatay, & Gomez, (2012).

Considering all three of these studies as a whole, it could come down to deficits in visuospatial attention, i.e. the inability to focus at each consecutive letter (target) present within a word (bearing in mind that the surrounding letters also add to the potency of distractor interference), the reason why majority of C&AwDys seem to suffer when the search displays and reading related material are crowded in nature. Thus, by increasing the interletter/word spacing, the features of neighbouring letters/words end up not being attended, thereby reducing or removing the effect of crowding altogether (better able to focus visuo-spatial attention).

1.6.6.3 Attention Span

Several studies have demonstrated a visual attention span deficit hypothesis in dyslexia, the paradigm which was initially coined by Valdois and colleagues (e.g. Valdois et al., 2004; Bosse et al., 2007; Bosse & Valdois, 2009). In order to entirely separate the influence of both visual and phonological processing in dyslexia, visual processing is this setting has normally investigated using change detection tasks using non-verbal material. For instance, Bosse & Valdois (2009) approximated the visual attention span by having the participants subjected to five different lettered consonant strings for a short space of time, where the participants were then required to respond by naming either as many letters as possible which was previously shown to them (global report) or just the matter of reporting a single target letter displayed on a validly-cued position (partial report). Findings from this study generally showed the same pattern whereby CwDys, in comparison to age-matched controls, had a significantly worse performance on both tasks. In addition to this, the CwDys showed severe difficulties when recalling the target digits concerning the global report task, with the deficit being attributed to possible demands in the maintenance and retrieval process (based on stored information within the working memory) rather than demands to cope with the partial report task. In addition to this, no sooner the authors controlled for phonemic awareness and verbal short-term memory (using multiple regression analysis), they immediately spotted that recalculated figure explained performance similar to that in the global report task. This finding alone was sufficient enough for the authors to confirm that the CwDys suffered from a reduced visual span. A large body of Valdois and his colleagues reported the exact same finding in other tasks which assessed visual attention span, for instance, simultaneous vs. sequential comparisons of global report (Lassus-Sangosse et al., 2008).

Studies which employed recognition thresholds along the letter strings resulted with somewhat mixed findings. In Hawelka et al (2006), the output they witnessed based on the recognition thresholds was an M-shaped serial function, indicative of both groups requiring even shorter task duration for presentation of the letter/digit at both the initial and final string positions. This pattern was regarded to be inconsistent given that dyslexics suffered from a narrowed visual attentional window. In fact, the W-shaped function was far more pronounced in the dyslexic group suggesting that they needed more time to view the targets letters at positions two and four, further suggesting that the dyslexics had undergone crowding effects based on the interference arriving from the surrounding letters. This was along the lines of Martelli et al (2009) having found poor performances in Italian CwDys (similar to that with controls) during single letter identification requiring larger spacing for target identification when surrounded by two distracting letters. Moreover, by means of partial reports using both forward and backward masks in a group of French children, Zeigler, Pech-Georgel, Dafau, & Grainger (2010) did not replicate the significant deficits at positions two and four as Hawelka and colleagues did. This resulted in Zeigler and colleagues having to decline the idea of dyslexics undergoing excessive crowding related difficulties. It was thought that this inconsistency could have come down to the operational mode of responding to a target. For instance, Hawelka and colleagues employed the reporting of a cued digit/letter which was actually open-ended. Comparing this with Ziegler and colleagues study, it was down to a choice where in which the participants were able to choose any one of two alternatives to make a response, with the incorrect alternative gotten rid of from the stimulus array, suggesting the a slimmest of chances in have detected an error as a result of mistakenly viewing it off the string. Nevertheless, a follow-up study by Collins, Kohnen, & Kinoshita (2012) took all these methodological concerns while putting a partial report task with five-letter, digit, and symbol strings to a test in a group of AwDys. This time round, there were more alternative response options, with findings revealing a poor overall performance in AwDys compared to matched controls in both letter and digit strings except for symbol strings, in addition to both groups producing the characteristic W-shaped serial function with letter and digit strings. As expected the deficits in the dyslexic group concerning letter string were limited with respect to the number of position errors (two and four). Furthermore, the observed findings correlated with letter transposition errors unlike with the RAN task, further suggesting a deficit in parallel processing of single letter strings.

Prado, Dubois, & Valdois (2007) took this one step further in studying whether eye movements of dyslexic and control readers were recorded in both the text reading and visual search tasks for immediate relevance for reading. The study was carried out on a subgroup of French CwDys known for a visual attention span disorder with intact phoneme awareness. Findings from this study reported a higher number of rightward and leftward fixations in the dyslexic group unlike the control group. Consistent with previous accounts, the findings did not disclose any group differences concerning eye movement patterns during visual search, with the exception of the consonant strings having the same visuo-spatial characteristics as text reading. More importantly, the visual attention span abilities with regards to the dyslexic group were equivalent to the number of letters processed concurrently during reading. Nevertheless, the abnormal eye movements of some (not all) dyslexic readers while reading did indicate that dyslexics do have difficulties when increasing their visual attention span based on tasks which demands them to do so. Findings along these lines were also observed in tasks assessing reading and copying (Bosse, Kandel, Prado, & Valdois, 2014) in addition to naming digits and dice (Pan, Yan, Laubrock, Shu, & Kliegl, 2013).

Thus, given the inconsistent findings above, it comes down to the type of paradigm utilized since string processing has been investigated in countless of ways in dyslexia, hence yielding contrasting results. It is crucial when considering studies of this nature to opt for a multi-element parallel visual processing strategy since not only will it need to process many items, the nature of visual processing needs to run in parallel. In studies that do not conform to this, there appears to be no limit on the presentation time (e.g. Hawelka & Wimmer, 2008). In one of the most recent studies conducted by Schneps, Thomson, Chen, Sonnert, & Pomplun (2013), they carried out what was a visual span task using a reading method called span limited tactile reinforcement (SLTR) where text messages gets displayed on a smartphone with larger fonts such that the text extends a few words per line. Using this method, AwDys were inspected to see if they could benefit from SLTR method, i.e. by overcoming difficulties in phoneme decoding and sight word processing. It turned out that they performed well than Schneps et al (2013) expected, given this method presented letters which were wide apart, in which case there was no sign of crowding affecting the results. The AwDys who found it hard to comprehend items were better when using the SLTR method than the conventional paper reading. This finding alone supports the presence of a poorly distributed attention span in dyslexia. The next sub-section should tell us how good individuals with dyslexia are at controlling and distributing their attention.

1.6.6.4 Control and Distribution of Attention

In order to perform any goal directed actions such as saccadic eye movements or even an action which requires a muscular response (e.g. reaching towards something on the bookshelf), one should be in a position to deploy and be accompanied by covert shifts of attention to the future target position. One way in which attention gets deployed (oriented) in an experimental sense, is via cueing strategies (e.g. pre-cues). Suppose deployment of attention is all perfect, there is another crucial aspect guiding accurate visual perception and that is distribution (shifting) of one's attention. This mechanism regulates the selection of relevant information, via a process of actively suppressing visual information from the unattended side. This act of shifting attention to one side of the visual field facilitates selection of information in that visual field.

Several research studies investigating the selectivity aspects of visual attention have related the poor multi-element processing performance in individuals with dyslexia to a discrepancy in the spatial distribution of attention (Facoetti & Turatto, 2000; Buchholz & Aimola Davies, 2005; Bosse et al., 2007; Ruffino et al., 2010). Spatial attention is considered to be important for nonword reading compared to normal word reading (Facoetti et al., 2006), the former requiring rapid serial left to right shifts of visual attention which necessitates the engagement of magnocellular (visual) processing system. The magnocellular system is one of two subsystems responsible for visual perception, with its input crucial for efficient functioning of the parietal cortex. The posterior parietal cortex is involved in peripheral vision, normal eye movement and spatial attention, which are all important in reading. Fluent reading of text requires flawless focusing, orienting and shifting of attention. That is, while one word is being currently fixated (target), a leftward-rightward shift of covert attention to the next word is of sole importance while maintaining focus on that particular target word. In addition, the perceptual spans being larger to the right of fixation aid the normal readers to benefit from parafoveal words during reading.

However within the dyslexia population, there is evidence to suggest that the perceptual span is atypical (Prado et al., 2007; Judge, Knox, & Caravolas, 2013) and such readers end up making smaller saccades during reading (Rayner, 1998; Rayner et al., 1998, 1989). Since smaller saccades are associated with text-reading difficulty, this in turn may be associated with smaller or atypical covert shifts of attention. In turn, such a difficulty may be more apparent in the right visual field due to leftward–rightward shifts of covert attention (Judge et al., 2013). Such impairments in shifting of attention constrain the amount of visual information which can be perceived on any given fixation. Brannan & Williams (1987) were the first to demonstrate deprived shifting of attention in poor readers. Thereafter, Carrasco & Yeshurun (1998) extended the previous findings using a letter cancellation task which involved searching for a target letter in a set of background letters (distractors) with detection accuracy measured as a function of set-size. The children with the lowest performance in this task read significantly slower than those with the highest performance, thus demonstrating a link between attention and reading achievements.

Facoetti and his colleagues (Facoetti et al., 2000a, 2000b, 2001, 2003a, 2003b, 2003c, 2005, 2006, 2008; Facoetti & Molteni, 2001; Facoetti & Turatto, 2000) demonstrated quite distinct functional abnormalities in terms of the ability to control/orient attention between individuals with dyslexia and normal reading controls. In one of the earliest studies by Facoetti, Paganoni, & Lorusso (2000a), the distribution of attention was measured by the time taken to detect a white dot target projected at different eccentricities from the fovea. Normally reading children showed a standard gradient of detection speed (the larger the eccentricity, the longer reaction times). In contrast, the eccentricity had no effect on reaction times of CwDys although they showed sluggishness of their automatic attention compared to control readers. To demonstrate this further, Facoetti, Lorusso, Paganoni, Umilta, & Mascetti (2003a) used so-called cue-size procedure where the target which was required to be identified was presented inside either a small or a large circle. The paradigm was such that, if the circle was displayed briefly before the target attention would automatically focus inside the circle. As a result, identification time was expected to be longer when the target was presented inside a large circle compared to the smaller circle. For CwDys, no effect of the circle size was found for the short (100 msec) cue-target interval although it was present at a longer cue-target delay (500 msec). In contrast, normally reading children showed a cue-size effect for both intervals. These results were interpreted as a manifestation of the sluggishness of automatic focusing of visual attention in CwDys.

Moreover, many studies have demonstrated that spatial attention is orientated asymmetrically both in C&AwDys using a variety of different tasks (Buchholz & Aimola Davies, 2005; Sireteanu et al., 2005; Liddle et al., 2009; Ruffino et al., 2010; Waldie & Hausmann, 2010; Ziegler et al., 2010). These authors suggested that the deviation in spatial distribution of attentional resources might account for reading errors such as omissions of letters/words and letter substitutions or transpositions. For instance, the study by Hari et al (2001) demonstrated a left–right visual field asymmetry in AwDys using two tasks, namely temporal order judgment and line motion illusion. For the former, two stimuli, one to the left and one to the right of the fixation point was presented. The line-motion phenomenon is an illusion in which a continuous horizontal line presented on the screen is perceived as an unrolling line if it is preceded by a peripheral cue. For this task, participants needed to indicate verbally the order of appearance, i.e. whether a given line moved from left to right or vice versa. It was found that in both tasks, AwDys responded more slowly when the stimuli on the left-visual field was displayed first (with findings also demonstrating this as a shortcoming in the "centre of gravity effect", see Crawford & Higham, 2001). On the basis of these results, Hari and colleagues hypothesized that

AwDys showed a left-side minineglect syndrome, i.e. a disadvantage of the left-visual field in selecting and processing visual information due to a smaller focus in the left, rather than in the right-visual field.

A very similar left-right visual field asymmetry of attentional resources was also observed by Facoetti and his colleagues (Facoetti & Molteni, 2001; Facoetti & Turatto, 2000; Facoetti et al., 2001, 2006). For instance, Facoetti et al (2001) investigated the control of attentional orienting in CwDys using a spatial cueing task consisting of two types of cues: valid (target appearing in the cued location) and invalid (target appearing the un-cued location), both presented either peripherally and centrally with participants' required to react to the target side. Faster reaction times in the valid cue condition indexed attentional facilitation (i.e. enhanced processing at selected location), whereas slower reaction times in the invalid cue condition indexed attentional inhibition (i.e. suppressed processing at unselected location). Based on the reaction time measures, for normal readers the typical cue effect was found, i.e. performance superiority of validly cued target over invalidly cued target and no visual field asymmetry. In contrast, CwDys showed no cue effect when the target was presented in the right-visual field. When the target was presented in the left-visual field, the cue effect was even greater in CwDys than in normally reading children. This "left mini-neglect" was attributed to a spatial bias leading to left-sided processing insufficiencies, equivalent to the more severe right-sided inattention which led the authors to suggest a specific deficit of the right attentional inhibitory mechanism in individuals with dyslexia, i.e. right PPC deficit. Facoetti et al (2006) also found that subgroups with impaired nonword reading lacked attentional inhibition to un-cued targets in the right-visual field and were slower at orienting attention in both visual fields at a very short cue (SOA = 100 msec), although this difference had resolved at 250 msec SOA (Facoetti et al., 2010). The authors confirmed that smaller orienting effects were as a result of attentional deficits due to the less efficient use of cue information.

However, there is some evidence which contradicts both the asymmetry in attention distribution and the theory of a right PPC deficit in dyslexia. For instance, using a string processing task, Hawelka, Huber, & Wimmer (2006) investigated the differences in visual processing between a group of German AwDys and age matched controls. The task had stimulus strings (five digits or consonants) presented briefly followed by a mask, thereafter requiring participants to report the digits. The findings demonstrated that the AwDys exhibited an advantage when reporting the first and last positions of the letter strings, which is inconsistent with the left mini-neglect hypothesis. In another study by Judge et al (2007), AwDys and control adults was tested using a simple cueing task and a saccadic version of the same task, the paradigm identical to that of Facoetti & Molteni (2001). In the cueing task, a target appeared 3°, 6° or 9° to the left or right of the fixation square. Participants were required to respond to the onset of the target with a button press. Their results showed that AwDys did not respond more slowly to the targets at the left-visual field than did controls. The second task of their study was identical to the cueing task, with the exception that participants had to move their eyes to the position where they believed the target had appeared. The results of the saccadic version of the cueing task revealed that AwDys were as accurate as the control group. The authors concluded that poor phonological skills in individuals with dyslexia underpin their literacy difficulties, and that in a simple cueing task their distribution of attention was normal. The authors further suggested that there might be a possibility that distribution of attention is asymmetrical in individuals with dyslexia only in childhood.

Nevertheless, further evidence against the mini-neglect hypothesis came from one of the earliest studies conducted by Polikoff, Evans, & Legg (1995) who investigated the visuospatial asymmetries between CwDys and normal reading children using a line bisection task. In the horizontal test condition both groups tended to transect slightly to the left of the midpoint, the result suggesting a small right sided neglect which, contrary to the current literature, is found here in participants with dyslexia as well as controls. This led the authors to conclude that right parietal lobe lesions are unlikely to be a common feature of dyslexia. Further to this, a most recent study conducted by Michel, Bidot, Bonnrtblanc, & Quercia (2011) measured the visuospatial asymmetries between CwDys and normal reading children using a similar method but in-cooperating a cueing paradigm consisting of geometric symbols placed on the extremities of the lines (rather than letter stimuli). Although, the bisection mark was shifted in the direction of the unilaterally cued extremities in both groups, the performance between control and CwDys was significantly different, with the former showing a leftward bias whilst the latter showed a rightward bias. Given this rightward bias in the spatial representation of CwDys, this by all means did not interfere with local context processing, prompting the authors to propose the term "inverse pseudoneglect".

Moreover, in an attempt to extend clinical and experimental findings from certain forms of reading disorders associated with spatial deviation in more severe dyslexics (e.g. those associated with parietal lobe lesions: Stenneken, van Eimeren, Jacobs, Keller, & Kerkhoff, 2008), a potential relationship between the extent of the spatial deviation and that of the reading disorder has not been addressed quantitatively. For instance, the earliest of studies into spatial distribution of attention were observed in unilateral neglect patients with a posterior brain damage. Patients with such damage may fail to orient towards or report information that appears on the side of space opposite the lesion. For example, individuals with dyslexia may copy/draw features only based from the ipsilesional side. Of importance for our consideration is the finding that neglect occurs more often and with greater severity in the right rather than left hemisphere lesions in humans, hence, demonstrating a remarkable left-right asymmetry. In support of the attentional hypothesis, some authors have therefore accepted a casual stand point where attention deficits in dyslexia is thought to be associated strongly with deficits of the magnocellular visual processing system (i.e. PPC dysfunctions: Facoetti et al., 2000a; Hari et al., 2001; Stein, 2003). However, there is evidence in contrary to this. Although visual field differences were not probed in the study carried out by Roach & Hogben (2004), the authors compared performance of AwDys on a visual search task with performance on tasks usually used to check functioning of the magnocellular system. While AwDys showed clear problems with visual search task (i.e. inability to use cues to exclude distractors), the magnocellular tasks were performed perfectly. This result can be viewed as evidence supporting an opposite causal link between magnocellular and attentional deficits. In other words, magnocellular deficits are due to the problems individuals with dyslexia have when it comes to attention concentration during task performance. It was shown that the poor performances of individuals with dyslexia in psychophysical tasks could be easily simulated by assuming some random responses caused by a number of subtle sensory (e.g. task difficulty) and non-sensory (e.g. lapses of concentration: Roach, Edwards, & Hogben, 2004, also see Stuart et al., 2001) contributions. In essence, Roach, Edwards, & Hogben (2004) proposed some tests which can help to distinguish between sensory and non-sensory contributions to poor performance by individuals with dyslexia. For example, given magnocellular deficits, there should be strict correlation among individuals with dyslexia between performances on different magnocellular tests. In other words, an individual with dyslexia who performs poor on one test should also perform poorly on another test. Roach et al (2004) stated "while multitask studies are becoming increasingly common, sufficient information to allow this comparison is seldom provided" (p. 825).

1.6.6.5 Signal Enhancement and Noise Exclusion

Several scholars have proposed various explanations of how attention improves perception in normal readers ranging from proper maintenance, deployment of attention, enhancement of the incoming visual information (signal enhancement), to those where attention improves the sensitivity by reducing external distraction (noise exclusion). Cueing attention to peripheral location has revealed noise exclusion to be the primary mechanism ahead of signal enhancement in spatial attention. Several studies have manipulated attention by means of central or peripheral pre-cues, the latter in a stimulus-driven fashion. Contrasting differences in the ability to orient attention have been observed based on the kind of cue utilised, valid when it 100% accurately indicates the target location, while considered invalid when it indicates a non-target location, or does not provide any indication whatsoever (neutral cue).Thus, by manipulating the validity of the cues, many studies have investigated the benefits associated with orientating attention. Therein, many studies have used this in an attempt to study the nature of attentional mechanisms and the levels to which they modulate visual activity in dyslexic individuals. Following the earliest of studies conducted by Facoetti et al (2000a) using a Posner-cueing task with a single dot stimulus, recent studies have also taken a step forward at investigating spatial cueing deficits between controls and dyslexia sufferers in terms of psychophysical thresholds using tilted targets. One such study is that conducted by Roach & Hogben (2004, 2007) using a search task (spatial-cueing paradigm) to assess the ability of AwDys to benefit from peripheral cues. It was found that AwDys benefit less from pre-cues than controls, suggesting poorer attention on the part of the AwDys readers. A study by Facoetti et al (2000) showed that AwDys weren't able to respond faster to cued targets compared to controls, the latter being able to respond faster to targets that were lead by a valid cue (80%). Both these findings indicate that the performance from AwDys shows neither a cost nor benefit from the presence of valid or invalid cues.

Sperling & colleagues (2005, 2006, 2007) questioned the magnocellular deficits in dyslexia suggesting that this may actually be a deficit in noise (distractor) exclusion. A classic study supporting noise exclusion deficits in AwDys is that conducted by Sperling et al (2005) with no cues being employed in their study. They tested both normal as well as CwDys capacity in utilizing stimuli that specifically activated either magnocellular (a patch containing white bars which rapidly rotated thereby inducing changes between light and dark) or parvocellular (identical patch to the magnocellular stimuli, but the white bars remained stationery and therefore did not alternate) pathways, in addition to two noise conditions (low and high noise). The contrast thresholds for both groups showed no difference for the low noise condition, unlike in the high noise condition where CwDys found it more difficult to detect both stimuli. Similarly, in a second follow up study comparing motion-direction discrimination thresholds, CwDys had a higher detection threshold in the presence of large external noise (Sperling et al., 2007), i.e. they did not suffer in low external noise conditions similar to controls. Sperling et al (2006) demonstrated strong links between linguistic abilities, age and the extent to which noise exclusion deficits were purportrated in a group of adults and children with/without reading problems. Whilst adult performances (hampered at high noise) associated with thier general abilty to read, childrens performances were strongly associated with all forms of linguistic abilities. In another recent study employing visual letter detection in conjunction with a search task (Beattie, Lu, & Manis, 2011), it was found that AwDys had higher thresholds than control adults in the presence of high external noise but not in the absence of external noise. According to the noise exclusion framework, normal readers were able to filter out the noise effectively so that the target information can be processed and then categorized or represented. However, individuals with dyslexia have a particular difficulty in perceiving visual signals in the presence of distractors as they are unable to effectively filter out distractors, which ultimately is thought to play a key role in reading problems in developmental dyslexia (e.g. poor categorization of letters). Studies have addressed this noise exclusion deficit in dyslexia within other sensory modalities (e.g. Chiat et al., 2007; Chandrasekeran & Kraus, 2009) and also ways in which such deficits were successfully overridden such as the use of image enhancing colour filters (significantly increased reading fluency by sharpening the contrast of the visual image dyslexics, e.g. Lawton, 2008; Northway, & Manahilov, 2010).

One approach to addressing the issue of signal enhancement has been to employ a spatial pre-cueing paradigm, in which participants' performance when a pre-cue alert them to the location of a to-be-presented stimulus is compared to their performance when the displays were left un-cued in displays containing varying set-sizes. Given a better performance whilst the stimulus location was validly pre-cued, this was typically taken as evidence for perceptual signal enhancement, the underlying mechanisms of which has been ascribed to the allocation of more attentional resources to the cued stimulus. A series of studies conducted by Roach & Hogben (2004, 2007, 2008) described psychophysical measures using a pre-cued vs. un-cued visual search paradigm requiring both the normal reading adults and AwDys to detect a tilted target stimulus amongst vertical distractors. Roach & Hogben (2004) inferred noise exclusion deficit in dyslexia using a single fixation visual search task where subjects were required to differentiate the orientation of the tilted target relative to varying numbers of vertical distractors at set sizes 1, 2, 4, 8 and 16, (eliciting varying external noise levels) present within the search array. The observed results of this study relates to two ends of the spectrum (**figure 17**). For un-cued targets, the resulting orientation discrimination thresholds showed no contrasting differences between controls and AwDys. For the pre-cued target stimulus, controls took immediate advantage of this cueing benefit unlike AwDys. Furthermore, AwDys demonstrated an inability to make use of the pre-cues on further addition of noise. It was therefore suggested that the cueing benefits observed in controls in all likelihood emulated late selection processes (at a decision level) compared to an early process (signal enhancement) of the incoming visual signal. In essence, this meant that the cueing deficit observed in dyslexia was likely due to poor noise exclusion at a (late) decision level. One other important finding in the study of Roach & Hogben (2004) is that psychophysical thresholds were also strongly dependent on the number of associative distractors present, thus yielding a set-size effect. This finding was similar to the outcome of several other studies showing elevated reaction times with increasing distractors (e.g. Bundesen et al., 2005). This set-size effect in the context of attention is at least partially attributed to sensory factors, in particular spatial resolution (Carrasco & Yeshurun, 1996, 1998). It has been shown that on increasing retinal eccentricity, a decrease in spatial resolution is concomitantly associated with an increased spatial uncertainty. Moreover, by pre-cueing target location Carrasco & Yeshurun (1996) found a strong eccentricity coupled with a more prominent set-size effect, whereby performance declined as the target appeared on increasing retinal eccentricities. This decrement in performance occurred on increase in set-size similar to that reported in Roach & Hogben (2004).

Figure 17: Cueing and set size deficits observed by Roach & Hogben (2004). (**a**) Examples of two stimulus arrays showing the set size manipulation employed. The small dot appearing in the periphery of the set size-16 array is the informative pre-cue whilst set size-4 array is un-cued. (**b**) The graphs illustrate the mean orientation discrimination thresholds when being cued and un-cued for both controls (left) and dyslexics (right.) Source: Roach & Hogben (2007).

1.7 Specificity of Attention Deficits to Literacy in Dyslexia

A number of studies have consistently found strong correlations between visual attention impairments and reading skill in samples of both normal readers and readers with dyslexia. For instance, an early study by Ruddock (1991) showed that CwDys exhibited a poor ability to perform a visual search task (identifying a target letter in a set of background letters) which was closely correlated with slower reading rate and a higher number of visual errors, suggesting deficits in selective visual attention. In line with this, the relationship between search performance and reading achievement was observed to be much stronger for tasks involving search for a conjunction of features (Buchholz & McKone, 2004) compared to a single feature (Facoetti et al., 2000a). Also, studies conducted by Sperling et al (2005, 2006) showed that AwDys in particular exhibited higher motion thresholds at a motion direction discrimination task (with varying levels of low and high background noise) only in the influence of high background noise, a finding which was closely correlated with slower reading rate. Similarly, studies have also pointed out strong correlations linking nonword reading capacity in CwDys to both the pace of attention shifting (Facoetti, et al., 2010) and the sluggish nature of attentional engagement and disengagement (Facoetti et al., 2008). The multi trace memory (MTM) model of polysyllabic word reading (Ans et al., 1998) is a framework which has raised a lot of support towards visual attention span deficits witnessed in dyslexia with impaired reading acquisition (i.e. prevents synchronized processing of letter elements tied to corresponding orthographic units). Moreover, the significance of visual attention span in reading has been very well emphasized using behavioural studies, with its performance observed to be a reliable predictor of reading performance in dyslexia (e.g. Bosse & Valdois, 2003). The above mentioned correlations point the way forward in terms of the strength a given deficit has on the capacity to read and write, which in turn provides much stronger evidence in favour of attentional difficulties in dyslexia.

However, the bigger picture of reading difficulties in dyslexia seems somewhat vague given the higher rate of co-morbidity that exists among different types of developmental disorders. A rough estimation has previously revealed that there are "impure/non-dyslexic" individuals than pure dyslexic individuals with visual attention deficits (Skoyles & Skottun, 2004). This was backed up by figures showing an estimated 15% of CwDys are also sufferers of ADHD, and around 36% of children with ADHD are in turn estimated to be potential dyslexic sufferers (Shaywitz et al., 1994). Some of the classic studies in the past have demonstrated the cognitive deficits within a sample of ADHD participants. It was not certain at the time as to whether this co-morbidity arose due to the common aetiology between the two developmental disorders (dyslexia and ADHD). It was only then Pennington, Groisser, & Welsh (1993) examined both phonological abilities and executive functions in a group of children with ADHD, together with a reading disability and a mixed group (having characteristics of both), with the authors proposing what was referred to as "phenocopy hypothesis". They proposed that instead of both disorders ending up with a common phenotype (e.g. Light, Pennington, Gilger, & DeFries, 1995) or one disorder being a trigger to the other in full, in fact it was claimed that one disorder could lead to symptoms of the other with the exception that the main characteristics of the secondary disorder would be generally absent. Roughly around the same period, Korkman & Pesonen (1994) came up with a comprehensive finding of a common developmental symptom present among three different conditions. They carried out a comprehensive set of neuropsychological assessments on three groups of children, each with pure ADHD, dyslexia, and ones with a specific learning disorder. Based on the measures, they found that children with specific learning disorders was impaired in phonological awareness, verbal memory span, attention control and verbal IQ, whilst both the ADHD and dyslexic participants shared similar deficits (i.e. attention control and verbal IQ, although the phonological awareness was only just within normal limits). This was the earliest of evidences linking ADHD and dyslexia, demonstrating that it can by all means result in attentional deficits.

Cognitive findings which were co-morbid in nature with dyslexia soon began to thrive in the child population and the numbers began to surge, especially with findings related to a common impairment in visuospatial orienting of attention (Swanson et al., 1991) in addition to an inattention to the left visual field (Nigg, Swanson, & Hinshaw, 1997). It was only then that a definition was coined for ADHD stating it to be a behavioral disorder with onset usually occurring in childhood characterized by lack of persistence, impulsivity, and excessive activity, with behavioral difficulties related to inattention to be one of the bases of ADHD diagnosis (American Psychiatric Association, 1994). The question one would like to ask is that, how does the strength of such a co-morbid factor (equating both dyslexia and ADHD) look approximately two decades following these initial findings. There is direct evidence that deficits on visuospatial attention tasks common with those of ADHD could be attributed to an inability to sustain attention to the task (Dobler, Anker, Gilmore, Robertson, Atkinson, & Manly, 2005; George, Dobler, Nicholls, & Manly, 2005). In the temporal domain, previous research with both C&AwDys have reported of prolonged attentional blink associated with ADHD (Armstrong & Munoz, 2003; Hollingsworth, McAuliffe, & Knowlton, 2001; Li et al., 2004) with findings of inattention observed on the left visual field (Jones, Craver-Lemley, & Barrett, 2008). However, there are number of studies suggesting that the attentional blink is not elongated in those with ADHD, compared to the controls (e.g. Carr, Nigg, & Henderson, 2006; Carr, Henderson, & Nigg, 2010; Mason, Humphreys, & Kent, 2005). Furthermore, the control groups in the studies suggesting impairment have been poorly characterized, i.e. those with ADHD have had co-morbid conditions, or those with ADHD have had difficulties with the baseline task or in the T1 identification component of the dual visual span task (Armstrong & Munoz, 2003). Li et al (2004) reported that double-deficits were found in children with ADHD similar to those having extreme levels of impulsivity (Li et al., 2005). Li et al (2004) proposed a theoretical model explaining both AB duration and AB minimum deficits in ADHD children which later was explained by the engagement and disengagement difficulties of dyslexic individuals (Facoetti et al., 2008). However, there are other studies having reported that not all individuals with ADHD suffer from such neuropsychological or cognitive deficits (e.g. Nigg, Willcutt, Doyle, Sonuga-Barke, 2005; Laasonen et al., 2012). Given the breath of findings in literature, it becomes even more important to use a test sample known to have none of the common co-morbid disorders, for which preliminary screening becomes very crucial.

1.8 Rationale

In summary, several studies performed with individuals with dyslexia (both in children and in adults) have gone on to report a number of attention related deficits. Using the discrepancy scores as a measure of the difference between the actual reading performance and the reading performance predicted from the individual’s intelligence score, group comparisons between dyslexic and non-dyslexic participants equated for reading ability have illustrated that the visual attention, despite being scattered (Facoetti et al., 2000a; Facoetti & Molteni, 2001; Facoetti & Turatto, 2000), is also under asymmetric control (Facoetti et al., 2001) in CwDys. Studies have in fact established deficits directly linked to dyslexia based on other aspects of attention. For instance, evidence of a sluggish attentional engagement and disengagement in both C&AwDys have been witnessed in tasks that cause shifting of attention to rapidly displayed stimuli such as attentional blink (Facoetti et al., 2008), attentional masking (Ruffino, et al., 2010), temporal order judgement (Liddle et al., 2009) and spatial cueing (Facoetti et al., 2010) tasks. Furthermore, spatial cueing tasks have also gone on to reveal cueing deficits (Roach &

Hogben, 2004), impaired filtering of distracting (noisy) visual information (Roach & Hogben, 2007), and attention orienting deficits (Buchholz & Aimola Davies, 2008) in AwDys. Similarly, serial visual search tasks have also identified a wide array of visual search deficits in both C&AwDys (Casco & Prunetti, 1996; Vidyasagar & Pammer, 1999).

Despite the extensive and yet promising findings from the literature regarding the nature of visual attention, there is still very little agreement regarding the processes which support selective attention of information, whilst rejecting the distracting information. In one account, Lavie & colleagues (2004) mentioned that the amount of attentional resources available determines the ability to process relevant information and prevent distractor interference. In a normal distractor-interference search task, it would be such that an observer gets bombarded with varying numbers of distractors simultaneously with the only target, the latter which is of concern to an observer. Unfortunately, there is only a limited amount of research within the visual domain which has been carried out in order to examine distractor interference when the presentation of distractor and target items are spatially separated.

Furthermore, many studies in the past which assessed deficits such as noise exclusion, crowding and attention asymmetry have predominantly focused on the child population, which makes inter-study comparisons between children and adults with dyslexia less effective. It has been argued that investigating language development at its later stages (i.e. older children and AwDys) disregards the progression of language attainment (Karmiloff-Smith, 1998). Nevertheless, instead of registering the development of reading fluency, this thesis aims to recognize exactly which cognitive processes goes on to influence reading performance. On a personal viewpoint at least, the use of adult participants seems far more appropriate for investigating issues of this nature. First, it is seemingly obvious that individuals with dyslexia find it hard when reading (e.g. Szenkovitz & Ramus, 2005), so it makes it that much more important that studies use non-linguistic stimuli to avoid any potential confound based on difficulties mirroring detection and/or discrimination of the linguistic stimuli. Furthermore, classifying performances between control and AwDys based on tasks employing reaction time measures is only going to make it highly susceptible to extraneous influences, a viewpoint similar to that of Wolf & Bowers (1999, p. 420). Another reason for basing this thesis on adult populations was to avoid conflation due to sensory factors (e.g. concentration, irritability, etc) especially with such factors being far more prominent in the dyslexic child population. This also served to minimise the risk of individuals being confounded by other co-morbid learning disabilities such as ADHD (e.g. Taroyan, Nicolson, & Fawcett, 2007). Even if these potential adult dyslexic participants do tend to possess hidden co-morbid disabilities, nevertheless, preventative measures are to be set in place where every participant under goes initial psychological screening (by a professional psychologist) in addition to reviewing dyslexic reports to familiarise their developmental history (based on other known disabilities). With majority of dyslexic adults coming from well established educational backgrounds, these participants would therefore be ideal given they are high-functioning (less compared to the control group) which is an absolute necessity, at least for the sake of comparison purposes.

One attempt to account for the observation of reading and phonological processing problems, coupled with occasional difficulties on visual and auditory processing tasks is the *external noise exclusion hypothesis (Sperling et al., 2005).* The fundamental idea is that the behavioral manifestations of dyslexia are at least partly due to a difficulty in excluding irrelevant (distracting) background information (referred as "noise" in this regard). Non-impaired readers would filter/exclude/suppress this noise so that the target information, or visual signal, can be processed and then categorized and/or represented. However, individuals with dyslexia are known for pursuing a particular difficulty when required to perceive visual (and auditory) signals in the presence of distracting information. According to the external noise exclusion hypothesis, the inability to effectively filter out noisy information results in poor categorization of letters (and sounds) which eventually manifests in reading related problems. While some studies have found evidence of a direct link between noise exclusion and reading (e.g. Boets et al., 2008), a handful of others have managed to find an indirect link to reading problems through general language abilities (e.g. Sperling et al., 2006). As a result, the exact nature of the noise exclusion deficits in dyslexia remains unclear.

The current research therefore seeks to find some valid answers based on how equipped and functioning the human visual attention system is in AwDys compared to age and IQ matched controls. Given the inherent noisy nature of distractors, the choice of paradigm used will be that of visual search, which offers the extra edge when having to manipulate the variables of interest in order to test a particular function. The current research will help probe two key mechanisms involved in visual selective attention, thereby highlighting how distracting irrelevant information is processed under varying task difficulty and noise conditions. The two attentional mechanisms of interest is that of signal enhancement and noise exclusion, both of which are known to be modulated by visual attention. Given the complexity of the paradigms in this research, the effect of visual crowding and attention distribution will also be investigated, but the key variable of interest is none other than of distractor (noise) exclusion.

1.9 Aims and Outline of the Thesis

Aims based on study 1 and 2 (Chapter 2 and 3):

(i) How successfully did AwDys use pre and post-cues to improve their performance?

(ii) Do the above differences between groups reflect processes occurring at the (late) decision level rather than an earlier stage when enhancing the signal via attention?

(iii) Are there differential spacing effects on search performance of non-linguistic stimuli between groups, and whether any effect can be modulated by attention?

Aims based on study 2 (Chapter 3):

(i) Are there any differential set-size effects on search performance for non-linguistic stimuli between groups, and whether any effect can be modulated by attention?

(ii) To what extent does influence of task difficulty (attentional capacity) limit search accuracy in AwDys compared to controls?

(iii) Do effects of cue use, crowding, and distractor exclusion (set-size) correlate with measures of literacy?

Aims based on study 3 (Chapter 4):

(i) Were AwDys able to exclude distractors efficiently in un-cued displays whilst spatial uncertainty was at its lowest (NB: the latter gave us the flexibility in gaining control over visual search whilst testing for only potential detection problems in AwDys)?

(ii) Were there differential visual field effects (left vs. right-VF) between groups and a possibility of it being a contributing factor towards poor noise exclusion in AwDys?

(iii) Do effects of set-size, attention distribution (asymmetry) and crowding correlate with measures of literacy (NB: by controlling for comorbid ADHD, we evaluated if ADHD among AwDys could explain their effects rather than pure dyslexia)?

Aims based on Chapter 5:

(i) Were there any dyslexic subtypes present? If so, what was the proportion of dyslexics that relate selectively to attention from that of pure phonological deficits?

Aims based on study 4 (Chapter 6):

(i) Were AwDys able to modulate visual attention efficiently in order to narrow down their attention focus so as to aid detection and discrimination of the target (faces) whilst ignoring the distractors?

(ii) What was the extent to which face fusiform area activity correlated with the behavioral measure of attention focusing for upright faces vs. inverted faces for both groups?

(iii) What was the cut-off angle of rotation (at nine angles between 0 - 315°) at which recognition performance for faces reduced to chance level in AwDys, compared to controls?

Chapter 2: Study 1

2.1 Introduction

Research into the pathogenesis of developmental dyslexia has lent significant support towards the potential role of visual functions. Evidence in support of this comes from studies concerning atypical motion perception and discrimination (e.g. Boets et al., 2011; Heim et al., 2010; Talcott et al., 2003; Witton et al., 1998), larger visual persistence (e.g. Lovegrove, Garzia, & Nicholson, 1990; Slaghuis & Ryan, 1999), deficient contrast sensitivity (e.g. Skottun, 2000), and unstable binocular fixation (e.g. Jainta & Kapoula, 2011; Stein, Riddell, & Fowler, 1988). In recent times, studies have also focused on a visual aspect known as "crowding" to play a key part in dyslexia. To recall, visual crowding refers to the deficit in identifying peripherally viewed salient element/s (i.e. targets) in the presence of nearby irrelevant elements (i.e. distractors). The cause behind the crowding effect hinges on a handful of theories from a lower level receptive field proposal to lateral masking (for a review see Levi, 2008), with such crowding studies being conducted predominantly within control populations.

One theory which has yielded a considerable amount of interest towards crowding is visual attention. Compared to central vision, the crowding effect in peripheral vision was found to be much larger as a result of a high-level processing occurring at the level of attentional selection rather than an early sensory level (e.g. Leat et al., 1999). Numerous studies have in fact explored the effects of covert attention, in addition to its functions in modulating and enhancing the control participants' ability to discriminate a target feature (from surrounding distractors) under crowded conditions (e.g. Chakravarthi & Cavanagh, 2009; Eriksen & Hoffman, 1972; Montaser-Kohusari & Rajimehr, 2005; Nakayama & Mackeben, 1989; Pelli et al., 2007; Posner, 1980; Yeshurun & Carrasco, 1999; Yeshurun & Rashal, 2010). Furthermore, Legge (2007) demonstrated a strong link between reading and visual crowding. Crowding during reading is regarded as the noisiness caused by the flanking letters on the recognition of target letters (inter-letters or intra-words spacing effects) and/or flanking words on the identification of target words (inter-words spacing effects), suggesting that crowding can occur both at a letter and a word level. Therefore, it is sensible to assume that individuals with dyslexia would suffer significantly from such crowding effects. Bouma & Legein (1977) classified letter confusability in a sample of CwDys, unlike in normally reading counterparts, using a flanker task. When the letters were presented in isolation, CwDys were able to recognise it similar to normal readers. However, as expected, the recognition performance was poor in CwDys when letters were flanked by surrounding letters when presented parafoveally, suggesting this to be a result of a deficit in attention allocation. Additionally, Lorusso et al (2004) aimed to verify the distribution of visual attention in Italian dyslexic and ordinary readers. The outcome of their results suggested a deficient narrowing in peripheral vision particularly in the right-VF for Italian CwDys, a finding which is in line with a general difficulty in having to inhibit distractor information especially when they are crowded.

However, unlike with controls (e.g. Dakin et al., 2009; Freeman & Pelli, 2007; Yeshurun & Rashal, 2010), not many studies have investigated the efficiency with which dyslexic individuals deploy their spatial attention (via attentional pre-cues) in order to check whether this served to diminish the effects of crowding in any way. Interestingly, alternative evidence from an orientation discrimination (search) task measuring psychological thresholds between control adults and AwDys have showed that AwDys, despite being able to detect and localize the pre-cue, found it difficult to cope with increasing numbers of distractors (Roach & Hogben, 2007, 2008). The authors proposed that the cueing benefits by controls in all likelihood indicated perceptual processing at a much later (decisional) stage, instead of visual information processing concerning a much earlier stage (i.e. signal enhancement). They further stated that the difficulty in pre-cueing portrayed by the AwDys may have been due to inefficient noise exclusion at a much later (decisional) stage. As mentioned in **section 1.6.5**, the two key components of spatial (peripheral) attention happens to be signal enhancement and noise exclusion, and therefore it becomes that much more imperative to investigate both these key attentional functions in a visual crowding setting (for the very first time).

2.2 Study Objectives

The question therefore remains, could AwDys, along with controls, modulate their attention so as to overcome the crowding effect? One thing to bear in mind is that, for attention to assist in modulating competition between two stimuli (target and distractor), the relevant visual incoming information must be readily filtered (with target features compared against distractor feature properties), hence reducing the need for excessive attentional resources. Moreover, for attention to assist in modulating target detection in a crowded versus a spreaded setting, stimulus set-size (i.e. number of attended items – target and distractors – at any one time) should therefore have no influence whatsoever on search performance.

This preliminary study focuses on deficits associated with AwDys in terms of spatial cue use, and exclusion of distractors (noise) to overcome crowding (referred to as "spacing") effects. In all facets of this study, much focus was adhered at eliminating all known limitations from previous research. Firstly, search performance in terms of accuracy measures was employed rather than reaction times in order to avoid influences from a combined sensory and attention factor. To achieve this, individual search performances was calibrated by constantly altering the duration at which the display array was presented. Furthermore, this enabled us to evaluate the extent to which attention was modulated across different experimental conditions, rather than contrasting the total performance achieved in both groups. By utilizing a simple orientation detection task using Gabor patches, phonological as well as letter identification difficulties in AwDys was eradicated. With the help of this protocol, we also attempted to dissociate a set of well known factors that could play a major part in the deficits currently known to dyslexia such signal enhancement and noise exclusion. The pre-cue vs. no-cue manipulation aimed to test for signal enhancement (i.e. exclusion of distractors at an early stage – before decision), whilst the post-cue vs. no-cue manipulation tested for noise exclusion (i.e. at the late decisional stage) respectively. This search paradigm also featured two levels of task difficulty (easy and hard), which allowed us to further examine the influence of attentional capacity limits on search accuracy in the presence of a crowded and spreaded displays.

2.3 Study Aims

To sum up, this study aimed at investigating two research questions of interest:

- Are there any differential spacing effects on search performance of non-letter stimuli between groups, and whether any effect can be modulated by attention?
- To what extent does influence of task difficulty (attentional capacity) limit search accuracy in AwDys?

2.4 Methodology

2.4.1 Participants

A total of 36 adult participants took part voluntarily in the current study. Of these were 19 controls having normal or corrected to normal visual acuity and 17 dyslexic sufferers diagnosed with either short and/or long-term specific reading difficulties, all of whom were predominantly right handed and native English speakers. These individuals were drawn randomly from a participant group actively involved in ongoing departmental research into visual attention and timing deficits at Aston University. Testing took place in two separate sessions (psychometric screening and experimentation) lasting roughly 1.5 – 2 hours for each participant. A monetary reward of £15 was offered upon completion of the study.

2.4.2 Preliminary Screening

2.4.2.1 Ethics

The current study was approved by the Department of Psychology Ethics Committee (Aston University). All participants were subjected to a short debriefing session at the very beginning which described the main procedures involved, so that they knew what to expect in this particular research study.

2.4.2.2 Risk Assessment and Informed Consent

Risk assessments were conducted during the preliminary stage of screening where the participants were informed of the risks and potential discomforts associated. The primary risk in this study was visual distress (due to the flickering nature of some of the visual stimuli used) especially if one suffered from a migraine or previously known cases of short/long-term epilepsy. To counteract this, participants were given an advance warning during the screening session and also informed that they were free to withdraw at anytime should they feel uncomfortable whilst carrying out the experiment. In the best interests of all participants, those having experienced recent epileptic seizure(s) and/or a migraine (i.e. during the screening stage or immediately before) were not allowed to take part in the study. To minimize any discomfort(s) due to visual stress, all participants were encouraged to have frequent breaks in between experimental blocks where specified.

At the third screening stage, the participants were required to submit an informed consent (see **Appendix 1**). As part of the consent, participants were advised that:

- Their participation in the study was completely voluntary.
- They may withdraw from the study at any time for any reason it may be.
- All personal information provided by them was held confidentially.
- Their data will be stored securely in a password protected computer, identifiable only by a unique participant number.
- Should the research study becomes publishable, all data would then be pooled and published in aggregate form only.

2.4.3 Standardised Psychometric Screening Tests

Three psychometric screening tests (IQ, spelling and word reading) were administered individually to each participant during the preliminary testing session. Participants who successfully conformed to the selection criteria were allowed to complete the experimental (spatial cued visual search) task.

2.4.3.1 IQ (Full scale)

Each participant within the dyslexic group had a formal diagnosis of dyslexia, with participants being asked to produce a recent psychological assessment report (from an appropriately qualified psychologist) at the time of screening[8]. With the WAIS–III (Wechsler Adult Intelligent Scale, Wechsler, 1999a) IQ estimate already available, this measure was used rather than having to re-administer the IQ-test (this further excluded any practice effects).

Unlike dyslexic participants, an IQ test was administered (by a trained member of staff) to all control participants using WASI (Wechsler Abbreviated Scale of Intelligence, Wechsler, 1999b). Each participant's cognitive capacity was approximated using the Verbal and Performance scale subsets. Tests for Vocabulary and Similarities produced an estimated score based on the verbal IQ. The Block Design and Picture Completion tasks produced an estimate of the performance IQ. In all cases, the inclusion criterion was such that the full-scale IQ was equal to or greater than 85.

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[8] The diagnostic assessment report for all AwDys indicated psychological test results which were conducted in their adulthood. Based on the psychological assessment report produced at the psychometric screening stage, none of the dyslexic participants had their most recent diagnosis conducted any longer than 6 years.

2.4.3.2 Spelling and Word Reading

Participants were pre-screened for their spelling and word reading to determine their intellectual performances and to also ensure that their progress scores were updated regularly within the participant database. Word reading and spelling tests were conducted according to the specifications instructed by the WIAT–II^{UK} (Wechsler Individual Achievement Test – Second UK Edition; Wechsler, 2005) testing manual. WIAT–II scores were compared to composite standard scores predicted from their IQ on the basis of their composite standard scores obtained from the sample.

- Spelling ability was assessed using the spelling subtest (Stimulus Booklet 1). The participants were required to respond to a target word (dictated by incorporating the target word into a short sentence) in writing. A total of 36 target words were read out to the participants leaving ample time to fully respond (this includes repeating the word once upon request), failing which the next word was read out (see **Appendix 2**).
- Word reading ability was assessed using the word reading subtest (Word Card). The participants were required to identify individual words from a list of 131 real words and respond as quickly as possible (see **Appendix 3**). Scores were attributed only for correct pronunciation and not comprehension.

The psychological assessment report produced by the dyslexic participants' also demonstrated evidence of enduring literacy difficulties (i.e. WIAT–II spelling and/or WIAT–II reading performance being significantly below a given individuals IQ). Unless otherwise the psychological assessment for dyslexia was carried out less than 12 months, both these literacy measures were re-administered during the screening session. Despite control participants having reported of no short and/or long-term difficulties with reading and spelling, nevertheless both these measures were administed during the psychometric screening session. The psychometric details concerning both the literacy (i.e. WIAT–II spelling, WIAT–II word reading) and IQ (full-scale) measures for the control and dyslexic groups are summarized in **Table 1**.

2.4.4 Apparatus

The spatial cueing search task was developed using the advanced psychology software E-Prime 2 (Professional Version)™. The experiment was run on a P4-Dell™ Optiplex GX 260 desktop computer displaying the output on to a 19-inch CRT monitor (Vision Master™ Pro 510) with the following custom specifications: screen resolution = 1024 x 768 pixels and refresh rate = 60 Hz. Prior to the experiment, the participants positioned their chin firmly on a chin rest which served to minimize any changes in head position during the experiment. This also ensured that the gaze was directed to the centre of the monitor i.e. at the central fixation point (**+**), while seated at a distance of 57 cm away from the computer screen. Both the practice and the main experiments were conducted in a dimly lit room maintained at a comfortable temperature, with participant responses made by specific key presses on a standard computer keyboard.

2.4.5 Experimental Stimuli

The stimuli employed in this experiment were obtained using the software Matlab™ (MathWorks Ltd). Each stimuli present on the search array were a set of gray scale, sine-phase Gabor patches generated by convolving a 2D circular Gaussian blob with a sinusoidal luminance grating (Foley et al., 2007). This was presented on a 64 x 64 pixel grid having a gray uniform field (luminance 28 cd/m^2) as indicated in the following equation (Gersch et al., 2004).

$$I_{(x,y)} = I_0\,(1 + c \sin(2\pi f(x cos\theta + y sin\theta)) exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right))$$

These Gabor patches comprised of wavelength, λ = 10 p/c (pixels per cycle)[9] and a Gaussian standard deviation or spread, σ = 10. The target Gabor's were tilted at two sets of difficulty, θ = -5°/+5° (easy condition) and θ = -2°/+2° (hard condition) relative to the vertical (**figure 18a** and **18b**). The distractors were absolutely vertical, θ = 0° (**figure 18c**) serving to distract the participants attention during the visual search task.

The cue (**figure 18d**) represented by the small circular black dot had a dimension of 0.8 degrees in diameter with a corresponding luminance of 1 cd/m^2. This cue was either presented at peripheral regions spanning 4° from the fixation point (with luminance 1 cd/m^2) or directly on top of the fixation point. Even though the cue signified target onset, the cue validity was such that when peripherally presented, it indicated the target location within the stimulus array with 100% accuracy (valid – pre and post-cue). Cues presented centrally did not (neutral – no-cue).

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[9] We attempted to create Gabor patches similar to that used by Roach & Hogben (2007). Since our study incorporated a "task difficulty" criteria, the Gabor patches created using λ = 3 p/c (as in Roach & Hogben, 2007) made it hard to spot differences between the easy and hard tilt. Since this cued paradigm involved both tilt detection and discrimination, it was necessary that the Gabor patches varied slightly in terms of tilt angles in order to pose a difficulty effect. Hence, λ = 10 p/c was opted.

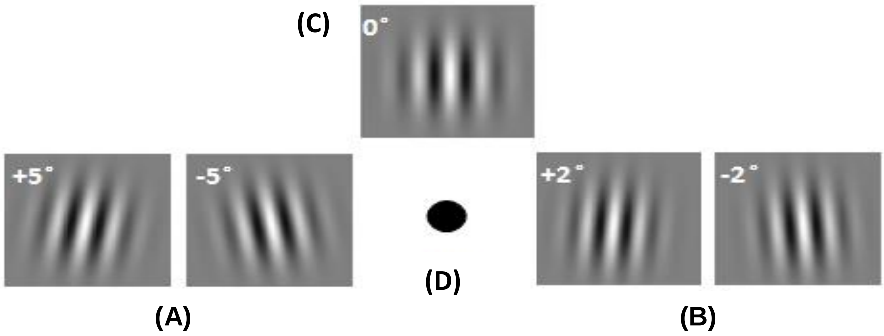

Figure 18: Stimuli present within the search array. Note the changes in tilt angle correspond to the level of difficulty (**a**) easy, and (**b**) hard. (**c**) Vertical distractor (**d**) Cue - Informative when peripherally located (valid cue) or non-informative when centrally located (neutral cue).

2.4.6 Set-size Configuration and Spacing

Eight Gabor patches (set-size 8) were positioned on the circumference of an imaginary circle 5° from the central fixation point (**figure 19**). Set-size 8 search displays were of two spatial configurations, namely spread (**figure 19a**) and crowded (**figure 19b**). Both the spread and crowded search displays consisted of eight stimuli (7 vertical distractors and 1 tilted target). Unlike the spread condition, the crowded search displays were arranged in the form of a semicircular arc extending to either one half (left or right-visual field) or both sides (left and right-visual field) of the display. The distance between adjacent Gabor patches (i.e. spacing) was varied accordingly, with 3.5° visual angle between each stimulus for the spread condition, reducing down to 1.6° in the crowded condition.

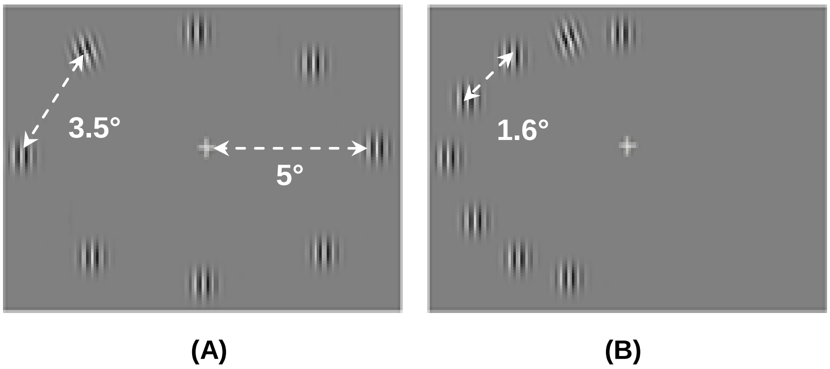

Figure 19: Stimulus spacing patterns. (**a**) A distance of 5° visual angle spans the central fixation point to a given target/distractor in both the 8-spread, and (**b**) 8-crowded display configurations. Note the changes in spacing between Gabor's despite the same set-size. There is only 1 tilted target surrounded by 7 distractors.

2.4.7 Study Design

2.4.7.1 Variables of Interest

Participants were required to indicate the orientation of the tilted target stimuli during a two alternative forced choice task. The probability at which these target stimuli appeared tilted either to the left or right was equally probable with each tilt associated with a given degree of task difficulty. These were present in both the set-size-8 spacing configurations which occurred 50% of the time during the entire trial sequence. Each cue appeared for one third of the trials. Taken together, these three independent variables gave rise to a total of 12 stimulus conditions of interest respectively, i.e.

- Cue type (pre-cue, no-cue and post-cue) = 3
- Spacing (8-stimuli evenly spread, and 8-stimuli crowded) = 2
- Difficulty (easy, i.e. -5°/+5°; and hard, i.e. -2°/+2°) = 2

For both the practice and the main experiments, the target stimuli as well as the order of conditions were varied randomly for all the participants.

2.4.7.2 Calibration of Stimulus Display

During the initial practice and calibration session, the display duration (200 msec by default) was tuned to each participant’s level of response accuracy before commencing the main experiment. In any block of 24 practice trials (2 trials for each condition), a reduction of 10 msec occurred when overall response accuracy surpassed 90% and the opposite was true when the overall response accuracy fell beyond 50%. This method of calibrating the response accuracy to the display duration ensured there was no saturation in performance (floor or ceiling effects), with the participants overall accuracy maintained within the 50% - 90% range[10]. Furthermore, the short working range of the stimulus display (110 msec by default ±10 msec) prevented any scanning eye movements during the visual search process.

2.4.8 Experimental Procedure

Figure 20 illustrates the sequences that took place in a single trial. Each trial sequence began with a blank gray screen with a central fixation cross **+** (initiated by a key-press). All

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[10] The average display durations of the AwDys and the control group differed significantly [176 msec vs. 92 msec, $t(31) = 10.837$, $p < .001$].

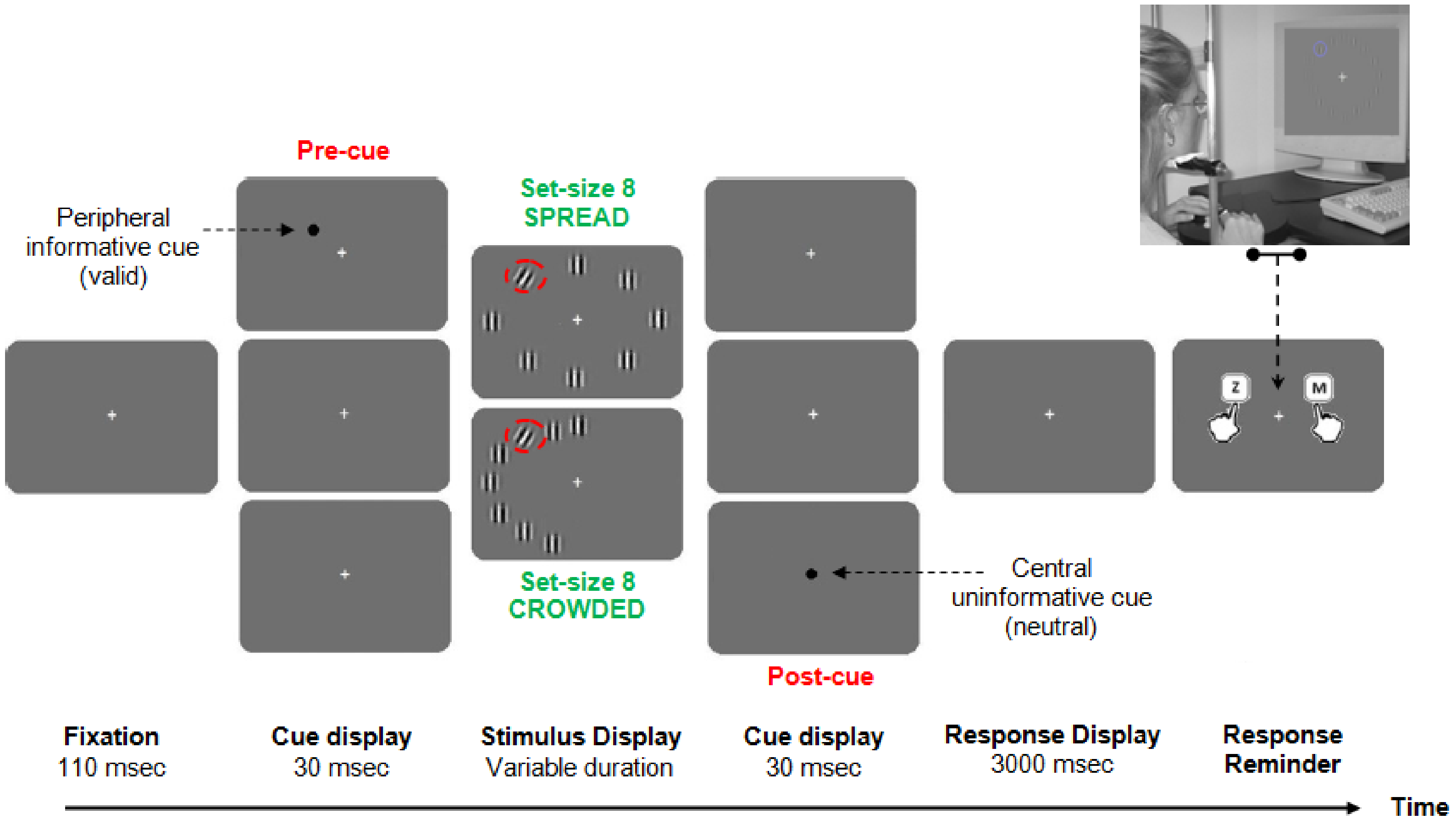


Figure 20: Schematic sequence of the visual search experiment in Study 1. Each trial had ONLY 1 of 3 cueing conditions: (a) **pre-cue** which indicated the precise location of the upcoming target, (b) **post-cue** which indicated the precise target location of the already presented stimulus containing the target, and (c) an **un-cued** display. The pre and post-cues were either valid (presented peripherally) or neutral (presented at fixation). The set-size-8 display was either spread or crowded. The target (as indicated by the dotted red circle) within the stimulus display is tilted to the right.

participants were instructed to fixate their eyes at this position right throughout the experiment. Each trial sequence consisted one of three random cues:

- **Pre-cue**: After initial fixation (110 msec), a brief pre-cue, either valid (peripherally presented informative cue indicating the precise location of the upcoming target) or neural (centrally located uninformative cue) was presented (30 msec). This was closely followed by a stimulus display containing the target and distractors (either set-size 8-spread or 8-crowded) presented for a variable length of time based on an individual's speed of accuracy (as per the calibration). This was immediately followed by a blank cue display (30 msec), thereafter permitting the participants to input their response.

- **Post-cue**: The sequence of events for the post-cueing trial is almost similar to the pre-cued trials, except that the cue display preceding the stimulus display was a blank fixation, whilst the cue display immediately after the stimulus display was replaced by a brief cue, either valid or neural (30 msec).

- **No-cue**: The control condition differed from the above two cueing manipulations in that, both cued displays (containing the pre and post-cue) was replaced by a un-cued blank fixation screen (30 msec).

Before completion of each trial, the participants were required to input their response to indicate whether the orientation of the target Gabor patch was to the left (by key pressing "Z") or to the right (by key pressing "M"). It has to be emphasised that the stimuli in this study were not masked (following the presentation of each stimulus display) unlike other studies described in the literature (e.g. Lev, Yehezkel, & Polat, 2014). With the help of the practice session(s), the participants came to terms that they were required to key-in their response within 3000 msec of the response phase. Failing to do so brought up a reminder screen requesting an input response for the target stimuli already presented. This screen acted as an "early pre-mask" for the follow-up trial immediately after the participant responded. Having this at the back of the participant's mind, not only were they expected to respond accurately (i.e. to the best of their abilities), but they were also expected to respond quickly enough, thereby minimizing any response bias.

In total, 15 blocks of 24 trials each were run for the main experiment requiring approximately 15 minutes per participant. All participants were offered short refreshment breaks and the chance to flex themselves in between experimental blocks, with an overall experimental duration lasting approximately between 15 – 20 minutes.

2.4.9 Statistical Analysis

One-way mixed design Analysis of Variance (ANOVA) in SPSS (version 12.0) were used to quantify if groups differed in age, IQ, WIAT–II spelling or word reading ability. These measures were further analysed using an independent samples t-test (equal variances not assumed, with 2-tailed significance levels). Mean percentage response accuracy data from the spatial cueing task was analysed using a two-factor ANOVA. The between participants factor was group (controls and AwDys) whilst the three within-participant factors were cue type (pre, post and no-cue), spacing (8-stimuli spaced, and 8-stimuli crowded) and task difficulty (easy and hard). Incorrect responses were excluded from the analysis. NB: Main effects were analysed prior to individual and group effects.

2.5 Results

The results section begins by looking at the differences in the outcome of the psychometric assessments for both groups. This is then followed by the investigation into the differences in cued visual search performances.

2.5.1 Psychometric Assessment

Following psychological screening, a control[11] participant along with two AwDys[12] were excluded, with both groups being closely matched for age (controls: M = 26.41, SD = 7.50, AwDys: M = 28.52, SD = 6.93) $F_{(1,\ 31)} = 0.83$, $MSE = 3.766$, $p = .372$, $\eta_p^2 = .11$, but not IQ (controls: M = 129.51, SD = 4.90, AwDys: M = 115.13, SD = 10.14) $F_{(1,\ 31)} = 20.19$, $MSE = 9.512$, $p < .001$, $\eta_p^2 = .41$. Compared to controls, AwDys showed a significant discrepancy in the standard score units for WIAT-II spelling (controls: M = 123.72, SD = 8.01; AwDys: M = 111.22, SD = 12.47) $F_{(1,\ 31)} = 17.87$, $MSE = 71.790$, $p < .001$, $\eta_p^2 = .59$. A similar pattern was also observed for WIAT-II word reading (controls: M = 119.32, SD = 5.20; AwDys: M = 106.73, SD = 9.28) $F_{(1,\ 31)} = 20.80$, $MSE = 62.446$, $p < .001$, $\eta_p^2 = .50$. The summary statistics of the preliminary screened data are presented in **Table 1**.

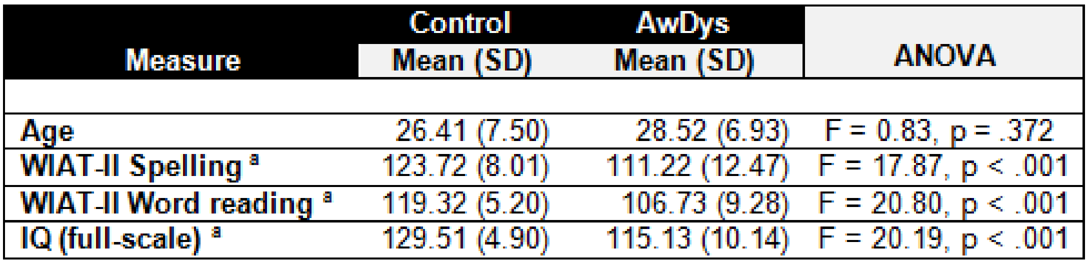
The exclusion criteria from the dyslexic group meant that a mean reading score at least 2 *SD* below the mean age level was required. On some occasions, control participants exhibited a significantly poor performance on either spelling or word reading. This occurred as a result of WIAT-II test hit the ceiling for age. Nevertheless, participants with an IQ below 85 were excluded in all cases.

[11] Scored significantly *higher* than predicted on both WIAT-II spelling and word reading.

[12] Scored significantly *lower* than predicted on both WIAT-II spelling and word reading.

Table 1: Demographic and psychometric group characteristics for Study 1. Data from a total of 18 controls and 15 AwDys data were utilized. Based on the statistics (mean scores, standard deviations and ANOVA results), findings demonstrated significantly poor literacy skills and IQ (full-scale) in AwDys compared to the control group.

[a] The composite standard scores (SS) predicted from IQ tests fell in range with the population mean ($M_{SS} = 100$, $SD_{SS} = 14$, and percentile rank = 50).



Measure	Control Mean (SD)	AwDys Mean (SD)	ANOVA
Age	26.41 (7.50)	28.52 (6.93)	F = 0.83, p = .372
WIAT-II Spelling [a]	123.72 (8.01)	111.22 (12.47)	F = 17.87, p < .001
WIAT-II Word reading [a]	119.32 (5.20)	106.73 (9.28)	F = 20.80, p < .001
IQ (full-scale) [a]	129.51 (4.90)	115.13 (10.14)	F = 20.19, p < .001

2.5.2 Differences in Cued Visual Search Performance

To re-cap, this preliminary study provided the opportunity to make use of the set-size-8 spacing manipulation in studying the effects of cueing, stimulus spacing (spread vs. crowded), and task difficulty on performance of both controls and AwDys.

2.5.2.1 Main Effects

In order to gain an insight of the inter-variable/factor relationships to follow, an overview of the overall main effects was first measured. A four-factor mixed ANOVA[13] of search performance was carried out with spacing (8-spread and 8-crowded), cue type (pre, post and no-cue) and task difficulty (easy and hard) being repeated factors.

The results showed a significant main effect of group ($F_{(1, 31)} = 30.94$, MSE = 0.006, $p < .001$, $\eta_p^2 = .42$), spacing ($F_{(1, 31)} = 33.27$, MSE = 0.008, $p < .001$, $\eta_p^2 = .52$), cue type ($F_{(2, 62)} = 30.24$, MSE = 0.002, $p < .001$, $\eta_p^2 = .49$) and task difficulty ($F_{(1, 31)} = 15.31$, MSE = 0.007, $p < .001$, $\eta_p^2 = .33$). Further to this, results showed a significant two-way interaction between spacing by cue type ($F_{(2, 62)} = 7.69$, MSE = 0.008, $p < .001$, $\eta_p^2 = .20$), and task difficulty by cue type ($F_{(2, 62)} = 4.26$, MSE = 0.011, $p = .026$, $\eta_p^2 = .22$) factors. A significant three-way interaction between spacing, task difficulty, and cue type emerged ($F_{(2, 62)}$ =

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[13] For those ANOVA's whose assumption of sphericity is violated (thus making an inaccurate F-test), a Greenhouse-Geisser correction was applied. The corresponding values of degrees of freedom were the same by default but the change in p-values occurred in line with the Greenhouse-Geisser correction.

5.11, MSE = 0.008, $p = .009$, $\eta_p^2 = .14$). No other effects or interactions reached any level of significance. These results suggest that the type of spacing effect observed within either (or both) groups was strongly dependent on the employed cue-type which failed to modulate attention, in addition to the difficulty of the search task at hand. These observed effects and interactions further generated the following questions of interest:

- Which groups showed a significant impact of spacing?
- How well were both groups at utilizing the cues to their advantage?
- How significantly different was cued compared to un-cued spacing dependent search performance?
- Was the increased task demand a performance limiting factor?

2.5.2.2 Individual Group Effects

The aforementioned effects and interactions (**section 2.5.2.1**) were then further analysed separately for each group to investigate whether control and AwDys approached the search task differently. The data from each group was subjected to a three-way ANOVA with cue type (pre, post and no-cue), display type (8-stimuli spaced, and 8-stimuli crowded) and task difficulty (easy and hard) as the within-participant factors.

Interestingly enough, a significant main effect of spacing ($F_{(1, 15)} = 14.88$, MSE = 0.003, $p < .001$, $\eta_p^2 = .46$) and task difficulty ($F_{(1, 15)} = 9.27$, MSE = 0.04, $p = .007$, $\eta_p^2 = .26$) was apparent in AwDys. In contrast, the main effects of spacing ($F_{(1, 18)} = 3.07$, MSE = 0.012, $p = .108$, $\eta_p^2 = .08$), and task difficulty ($F_{(1, 18)} = 4.60$, MSE = 0.010, $p = .084$, $\eta_p^2 = .20$) failed to reach significance in controls. However, the effect of cue type mattered for both controls ($F_{(2, 34)} = 7.18$, MSE = 0.009, $p < .001$, $\eta_p^2 = .30$) and AwDys ($F_{(2, 28)} = 21.81$, MSE = 0.007, $p < .001$, $\eta_p^2 = .61$). Furthermore, the two-way interactions between spacing by cue type ($F_{(2, 28)} = 8.88$, MSE = 0.003, $p < .001$, $\eta_p^2 = .39$), and task difficulty by cue type ($F_{(2, 28)} = 6.73$, MSE = 0.009, $p < .019$, $\eta_p^2 = .33$) did have a quite significant effect in AwDys, unlike in controls. Similarly, a significant three-way interaction between spacing, task difficulty and cue type was observed in AwDys ($F_{(2, 28)} = 5.22$, MSE = 0.006, $p = .021$, $\eta_p^2 = .22$), but not in controls ($F_{(2, 32)} = 1.42$, MSE = 0.015, $p = .138$, $\eta_p^2 = .08$). These results suggest that in AwDys, the degraded search performance (especially in the crowded condition) was therefore influenced by the severity based on the type of cue employed (i.e. information content of the cue), and the difficulty associated with the task.

2.5.2.3 Cue Use and Shifting of Visual Attention

Having had a look at the main effects of set-size-8 manipulation, an interesting factor which emerged in light of the current research was the cueing by spacing interaction observed in AwDys. Previous studies by Roach & Hogben (2004) had proposed a cueing deficit present amongst AwDys. This section re-examined if this was exactly the case in AwDys by investigating the effects of each cueing manipulation (i.e. pre vs. no-cue, and post vs., no-cue). The data from each group was therefore subjected to a three-factor ANOVA separately for each cueing and spacing manipulation, with cue type (pre vs. no-cue, and post vs. no-cue) and task difficulty (easy and hard) as repeated factors. This was done in order to investigate whether control and AwDys utilized the pre and post-cues differently throughout each spacing manipulation.

Based on the analysis for the pre vs. no-cue condition (i.e. by pre-cueing the cue display), a significant cueing effect was observed for controls only at the set-size 8-crowded condition, $F_{(1,\ 18)} = 10.31$, MSE = 0.006, $p = .031$, $\eta_p^2 = .38$ (**figure 21a bottom left**). However, with AwDys, a significant cueing effect was observed both at the 8-spread ($F_{(1,\ 15)} = 7.11$, MSE = 0.005, $p = .020$, $\eta_p^2 = .34$ – **figure 21a top left**) and 8-crowded ($F_{(1,\ 15)} = 32.86$, MSE = 0.002, $p < .001$, $\eta_p^2 = .70$ – **figure 21a bottom left**) conditions. Furthermore, in AwDys, a significant cue type by task difficulty interaction ($F_{(1,\ 15)} = 7.21$, MSE = 0.008, $p = .019$, $\eta_p^2 = .39$ – **figure 21a bottom right**) observed in the crowded display meant that AwDys weren't able to cope with increased task demands given the harder tilted target presented on crowded displays.

Based on the analysis for the post vs. no-cue condition (i.e. by post-cueing the cue display), AwDys showed no significant cueing effects in either set-size 8-spread ($F_{(1,\ 15)} = 1.76$, MSE = 0.018, $p = .089$, $\eta_p^2 = .09$ – **figure 21b top left**) or 8-crowded ($F_{(1,\ 15)} = 1.59$, MSE = 0.012, $p = .102$, $\eta_p^2 = .16$ – **figure 21b bottom left**) conditions. However, in controls, such a significant cueing effect was observed only in the set-size 8-crowded condition ($F_{(1,\ 18)} = 5.41$, MSE = 0.004, $p = .024$, $\eta_p^2 = .25$ – **figure 21b bottom left**). These results suggest that the level of task difficulty seemed to have not played a significant part as both groups were able to tolerate increased task difficulty when the display was spread (**figure 21b top right**).

The aforementioned results also indicate that controls used both the pre and post-cues (the latter to a much lesser extent compared to the pre-cue) for their advantage, whilst AwDys utilized just the pre-cue (and not the post-cue) predominantly in the crowded condition independent of task difficulty.

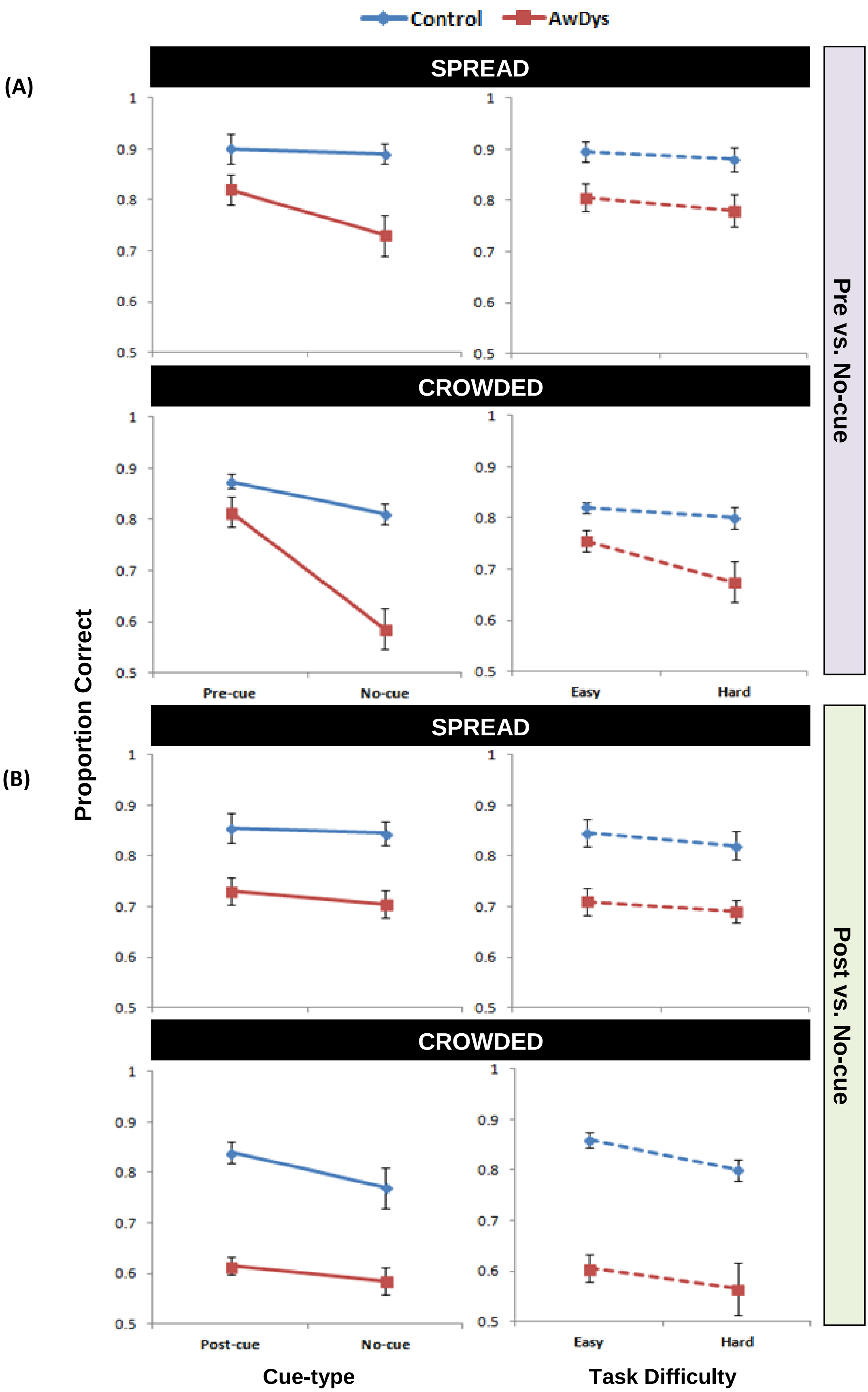


Figure 21: Proportion response accuracy based on cueing manipulations (**a**) Pre vs. No-cue, and (**b**) Post vs. No-cue; spacing (spread vs. crowded – horizontal panel); and task difficulty (easy vs. hard – vertical panel). Error bars represent ±1 standard error of the mean percentage response accuracy.

2.5.2.4 Effect of Cues on Spacing

With both groups using all three cues differently, the overall spacing effect was investigated further for the pre-cued trials (given both groups utilized it more compared to the post-cue) and how differently the performance varied when the displays were left un-cued in both groups. Post-hoc analyses were conducted separately for pre and un-cued conditions using a two-factor ANOVA with set-size 8-spacing (spread and crowded) and task difficulty (easy and hard) as the repeated factors.

When pre-cued (**figure 22 – left panel**), controls showed no significant effect of spacing ($F_{(1,\ 18)} = 4.29$, MSE = 0.006, $p = .093$, $\eta_p^2 = .16$) similar to that in AwDys ($F_{(1,\ 15)} = 1.18$, MSE = 0.014, $p = .198$, $\eta_p^2 = .12$). Furthermore, neither group showed any significant effects of task difficulty (controls: $F_{(1,\ 18)} = 4.36$, MSE = 0.007, $p = .074$, $\eta_p^2 = .17$; AwDys:

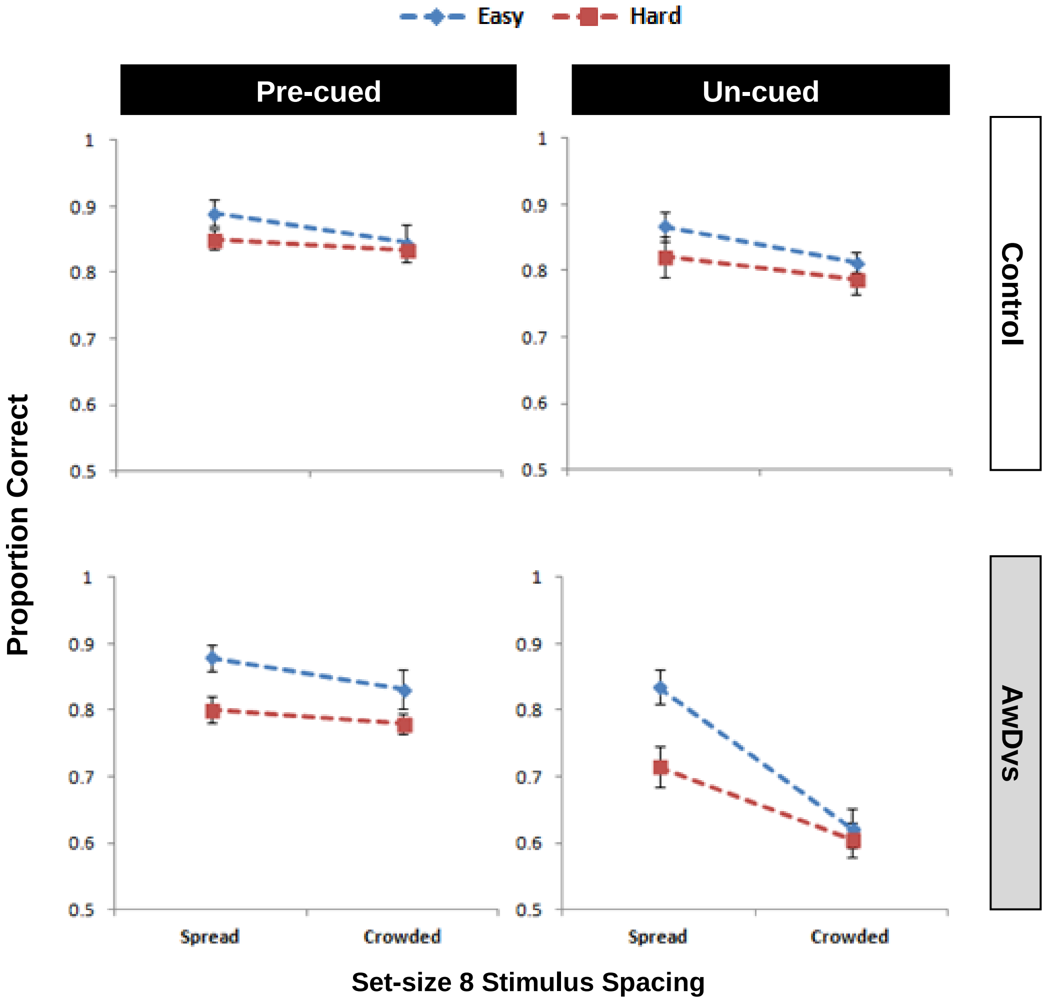


Figure 22: Spacing effects as a function of cueing and task difficulty. Unlike controls, in AwDys, performance drops significantly at crowded conditions when the stimulus search array is un-cued. Error bars represent ±1 standard error of the mean percentage response accuracy.

$F_{(1, 15)} = 4.57$, MSE = 0.010, p = .083, $\eta_p^2 = .14$) or a spacing by task difficulty interaction (controls: $F_{(1, 18)} = 3.48$, MSE = 0.009, p = .088, $\eta_p^2 = .07$; AwDys: $F_{(1, 15)} = 0.56$, MSE = 0.012, p = .474, $\eta_p^2 = .04$). An identical pattern of effects was observed for both groups when post-cued, except the fact that the effect of spacing narrowly missed significance for AwDys ($F_{(1, 15)} = 1.48$, MSE = 0.008, p = .058, $\eta_p^2 = .08$).

When un-cued (**figure 22 – right panel**), the control group showed no significant effect of spacing ($F_{(1, 18)} = 0.64$, MSE = 0.009, p = .439, $\eta_p^2 = .04$). However, AwDys did demonstrate a significant effect of spacing ($F_{(1, 15)} = 32.5$, MSE = 0.002, $p < .001$, $\eta_p^2 =.70$) in addition to task difficulty ($F_{(1, 15)} = 17.46$, MSE = 0.004, $p < .001$, $\eta_p^2 =.51$). Compared to the controls ($F_{(1, 18)} = 0.98$, MSE = 0.008, p = .34, $\eta_p^2 = .06$), a significant two-way interaction emerged between spacing and task difficulty in AwDys ($F_{(1, 15)} = 9.95$, MSE = 0.002, $p < .001$, $\eta_p^2 = .39$).

These findings suggest that when the search array was un-cued, AwDys showed a pronounced effect of spacing. Furthermore, given the easy conditions, still for all, the performance levels dropped significantly when the stimulus display was crowded. This goes to show a lesser impact of task difficulty on search performance in AwDys. Importantly, the performance of both AwDys and controls differed significantly when the stimulus display was un-cued and crowded. That is, AwDys were predominantly cue dependent and in the absence of a (valid) pre-cue, their overall modulation plummeted below threshold.

2.6 Summary Discussion

The present study compared control adults and AwDys on an orientation discrimination (search) task with fixed number of distractors presented at varying locations from the target stimulus across two spatial configurations. This study assessed the ability of both participant groups to utilize three visual cues (pre, post and no-cues) at overcoming the effect of spacing (spread vs. crowded) when further influenced by fluctuating task demands (easy vs. hard). The current study chiefly questioned the relevance of visual attention in crowding tapping directly on functions such as signal enhancement and noise exclusion.

The findings from this study showed that AwDys had decreased performance when distractors were placed closer together, despite having successfully utilised the pre-cues to enhance the target signal no matter how crowded together the stimuli were. However, they weren't able to use post-cues (with no difference shown to un-cued conditions) in order to successfully exclude the external noise. The crowding effect in AwDys suggests a possible deficit associated with attention allocation. This finding replicates those reported in studies using control participants, whereby pre-cueing (i.e. directing attention) a target location ameliorated the effects of crowding leading to a better overall performance in crowded displays (e.g. Chakravarthi & Cavanagh, 2009; Felisberti et al., 2005; Pelli et al., 2007; Scholari et al., 2007; Strasburger, 2005; Yeshurun & Rashal, 2010). Same was true in studies carried out with dyslexic individuals (both children and adults) using letter and complex letter like stimuli (e.g. Atkinson, 1991, 1993; Bouma & Legein, 1977; Callens et al., 2013; Martelli et al., 2009; Pernet et al., 2006; Speinelli et al., 2002). For instance, studies into visual crowding in dyslexia have demonstrated slower processing of both letter and symbol stimuli when surrounded by distractors, but not when present on their own (Speinelli et al., 2002). Speinelli and colleagues reported that the effect of crowding was nullified with gradual increase in the inter-letter spacing. With Pelli & colleagues (2007) having demonstrated a strong association between visual crowding and poor reading rates in control readers, Martelli et al (2009) further confirmed this relationship with CwDys given the sluggish rate of word analysis. Martelli and colleagues concluded that the limited identification of a letter target within multi arrays across a given visual field is due to significant crowding effects, resulting in a poor development of rapid reading skills. This was in line with the outcome of Callens et al (2013) when a strong correlation between the degree of crowding and word-reading ability became evident in a group of AwDys, unlike the controls. Therefore, the bottom line underlying an improvement in the reading ability is the enhancing capability of visual attention at the attended location leading to an improved description of the target. The effectiveness of this is signal enhancement in AwDys as reflected by the pre-cueing advantage.

The question therefore arises, would AwDys perform relatively to the same extent when subjected to varying external noise (distractors)?

Chapter 3: Study 2

3.1 Introduction

Several studies in the past have accounted for theories underlying deficits found in individuals with dyslexia (for review, see Démonet, Taylor, & Chaix, 2004). The most compelling of these was the phonological deficit theory (e.g. Ramus et al., 2003; Vellutino et al., 2004; Zeigler et al., 2008, also see **section 1.5.1**). However, more recently there has been mounting evidence towards an underlying connection between non-linguistic processes such as visual attention to the basis of reading difficulties in dyslexia (Vidyasagar & Pammer, 2010). Efficient reading relies on an optimum capacity to analyse letter and word strings using attention (i.e. sustained and focused) which is essentially rapid and accurate in controlling for visual orienting. By comparing participants with and without reading difficulties, evidence in relation to visual attention have revealed: (i) deficits concerned with automatic orienting of spatial attention (e.g. Facoetti et al, 2002), (ii) prolonged capture by attentional resources resulting in sluggish engagement and disengagement of attention (e.g. Facoetti et al., 2008), (iii) impaired filtration/exclusion of distractors (e.g. Sperling et al., 2006), (iv) diffused mode of attention distribution (e.g. Sireteanu, Goertz, Bachert, & Wandert, 2005), (v) asymmetric control of attention (e.g. Facoetti et al., 2001), (vi) special cueing deficits (e.g. Roach & Hogben, 2004), (vii) attention orienting deficits leading to weaker adjustment in the size of attentional focus (e.g. Buchholz & Aimola Davies, 2008), and (viii) attention span deficits (e.g. Lobier, Zoubrinetzky, & Valdois, 2011) measured using a variety of tasks (e.g. cued visual search, line bisection). Therefore, it’s plausible that impairment in any one or any combination of these attention processes may underlie problems with individuals with dyslexia when it comes to directing visual attention on separate letters in words, eventually leading to problems with reading.

Two important aspects of visual attention needs special mention, namely attention orientation, attention focusing and distractor (noise) exclusion, the subject of current investigation.

3.1.1 Attention Orientation

Prior to combination of letter-to-speech sounds, it is crucial that the given target letter(s) are accurately selected from irrelevant (distracting) surrounding letters via rapid orientation of visual attention. Contrasting differences in the ability to orient attention between study groups have been observed based on the kind of cue utilized in a Posner task (Posner, 1980). A pre-cue is generally considered to be *valid* when it 100% accurately indicates the target location (**study 1**). However, it is considered *invalid* when it indicates a non-target location, or *neutral* when does not provide any indication whatsoever (**study 1**). Thus, by manipulating the validity of the pre-cues in particular, many studies in the recent past have gone on to investigate benefits associated with orientating attention (i.e. shifting the attentional focus between visual fields). The earliest of these tests investigating the effect of pre-cueing attention on reading ability, utilized English letter targets as a probe to test for spatial cueing effects between controls and CwDys (Brammam & Williams, 1987). By peripherally pre-cueing letter targets presented at SOAs of 100 msec or less, controls showed a higher rate of letter detection accuracy in addition to a significant cueing effect unlike with CwDys, with the authors implying that such performance by the CwDys reflected neither a loss or gain regardless of the type of cue used. Conversely, a study replicating the same cueing paradigm, with the exception of a neutral dot cue, demonstrated a cue validity effect in CwDys given the higher reaction times (300 msec) when the cue appeared peripherally. A cue-validity effect was also observed much later in AwDys (Buchholz & Aimola Davies, 2008). Furthermore, Roach & Hogben (2004) using a spatial-cueing paradigm assessed whether dyslexic readers benefitted from peripheral cues. It was reported that AwDys benefited less from pre-cues than controls did, an indication of poorer orientation of attention in adult dyslexic readers. Facoetti et al (2001) by employing pre and no-cues investigated attention orientation using a two-choice reaction time task. Findings from this study showed a significant flanker effect when orienting attention towards the target location using pre-cues (unlike the no-cue), but the absence of this flanker effect was evident once the attentional focus shifted to the un-cued distractor location. The authors explained these findings in terms of facilitation (enhancement) and inhibition (exclusion) processes present at an early stage of visuospatial selection.

3.1.2 Attention Focusing and Distractor Exclusion

As much as attention orientation becomes important for reading, another key function of visual attention (once successfully orientated) is to modulate the size of its focus so as to accommodate the minimum quantity of visual information required for processing. The cue-validity effect as observed by Buchholz & Aimola Davies (2008) was therefore considered to be a difficulty in reducing the width of the attentional focus in AwDys, despite their ability to utilize pre-cues in order to enhance the target signal. Many studies in the past have assessed the degree to which dyslexic individuals, compared to control participants, were able to perceive visual signals in the presence of external distractors. The first of these studies carried out by Sperling & colleagues (2005, 2006) questioned the magnocellular deficits in dyslexia (e.g. Laycock & Crewther, 2008) suggesting that it may actually be a deficit in noise exclusion. Their study which employed a motion coherence task showed that CwDys performed as well as normal children under no-noise conditions, but was significantly less successful in identifying the target (motion direction) in conditions where there was high noise. Moreover, this poor performance in high noise conditions was a characteristic of weaker reading ability in CwDys. Roach & Hogben (2004, 2007) further ascribed a deficit in noise exclusion using psychophysical measures in a visual search paradigm. With control and CwDys required to detect a tilted target stimulus amongst vertical distractors, accuracy levels of both groups showed a parallel increase in threshold with increasing set-size especially when targets were un-cued. The normal readers were able to overcome the set-size effect when the location of the target was cued, unlike AwDys. The authors suggested that the cueing benefits demonstrated by the controls in all likelihood reflected perceptual processing at a later (decision) level, rather than a processing involving visual signal enhancement at a much earlier level (also see Beattie, Lu, & Manis, 2011).

3.2 Study Objectives

The present study offered a strong working hypothesis to further elucidate the deficits associated with AwDys in terms of their ability to (i) orient attention, (ii) focus attention, in addition to the (iii) working limits of two key attention processes, i.e. signal enhancement and distractor (noise) exclusion. The current study extends from study 1 (Chapter 2) with the inclusion of other conditions of interest.

- Despite the fewer crowding studies in dyslexia, most studies have favoured the use of letter or complex "letter-like" stimuli when investigating crowding effects (e.g. Martelli et al., 2009). The use of letters (e.g. Brammam & Williams, 1987) vs. non-letters (e.g. Buchholz & Aimola Davies, 2008) as stimuli in studies investigating attention functions has yielded conflicting findings given several variants of poor performances within the dyslexic population. For instance, Skottun & Skoyles (2007) evaluated instances where effects of inattention could be erroneously ascribed to sensory deficits. It is postulated that this mainly comes down to the difficulty in which dyslexia sufferers have when recognising letters. By using simple non-linguistic stimuli, the current search task (similar to that conducted in study 1) offered an advantage of accurately controlling for sensory aspects known to influence overall performance.

- Although study 1 attempted to dissociate both attention functions (i.e. signal enhancement and noise exclusion) based on the extent of cue use (i.e. pre vs. post-cue), the noise present within the system may have not been ideal given that there was no variations in external noise (i.e. distractor numbers). The current study aimed to rectify this by the inclusion of a varied batch of stimulus set-sizes (1, 8 and 16).
- Some studies have not excluded alternative explanations of a given paradigm which further paved way at generating incompatible results. A good example of this is that of Roach & Hogben's (2004, 2007) visual search paradigm. In their study, whilst a large cueing difference was observed between cued and un-cued performance in both controls and AwDys, this difference was quite evident at larger set-sizes. Larger set-sizes have been generally accustomed at yielding major benefits by peripherally pre-cueing the search array. However, as per Roach & Hogben's paradigm, any increase in the set-size equated to more stimuli (distractors) being placed progressively close together. Hence, the final outcome of their study could have been actually due to an influence of visual crowding, rather than a pure set-size effect. The current study therefore differentiated both these effects by: (i) varying the number of distractors whilst keeping the inter-stimulus distance constant, i.e. set-size effect, and (ii) varying the inter-stimulus distance whilst keeping the number of distractors constant, i.e. spacing effect. For this reason, the spacing vs. crowding condition was the same as that used in study 1, giving the added advantage of being able to confirm the crowding effect from study 1.
- Studies investigating attention orientation, in many cases have opted for reaction time measures (e.g. Facoetti, 2001). The purpose behind identifying attention deficits associated in dyslexia is to identify the capacity at which dyslexia sufferers orient their attention, rather than it being the case once oriented. Moreover, delayed reaction times could also be a sign of problems in signal enhancement and/or noise exclusion once oriented, instead of an orientation deficit. Although study 1 comprised of accuracy measures, it was even more important for the current study to also measure

search performance in terms of accuracy, given that one of the key aims of the current study was the orientating capability by both participant groups.

The pre-cue (i.e. test for signal enhancement and early exclusion of distractors) vs. post-cue (test for late noise exclusion only) manipulations remained identical to that conducted in study 1. Also, when a small feature such as a difference in orientation defines the target (tilted) from the distractor (vertical), detection of a target element becomes substantially slowed on increasing set-size, an effect which is closely attributed to attentional capacity limits (e.g. Huang & Pashler, 2005). Moreover, worse performance observed in dyslexic individuals' was either thought to reflect problems in regulation of task demands (Badcock, Hogben, & Fletcher, 2008), instead of a core (Buchholz & Aimola Davies, 2007) or an explicit (Lum, Conti-Ramsden, & Lindell, 2007) deficit in dyslexia. Therefore, similar to study 1, the search paradigm in the present study also featured two levels of task difficulty (easy and hard) so as to examine the influence of attentional capacity limits on search accuracy. Given the calibration similar to study 1 (Chapter 2), the extent of attention modulation across different experimental conditions was evaluated rather than contrasting the total performance achieved in both groups.

3.3 Study Aims

This study aimed at investigating the following research questions of interest:

- Are AwDys successfully able to use both pre and post-cues in order to improve their performance?
- Therefore, do the above differences between AwDys and controls reflect processes occurring at the (late) decision level, rather than an earlier difference in using attention to enhance the visual signal?
- Are there any differential spacing effects on search performance of non-letter stimuli between groups, and whether any effect can be modulated by attention?
- Are there any differential set-size effects on search performance of non-letter stimuli between groups, and whether any effect can be modulated by attention?
- To what extent does influence of task difficulty (attentional capacity) limit search accuracy in AwDys?
- Do effects of cue use, crowding and distractor exclusion (set-size) correlate with measures of literacy?

3.4 Methodology

3.4.1 Participants

A total of 33 adult participants (17 controls and 16 AwDys) took part voluntarily. Of the participants who took part in study one, 10 controls (4 males) and 12 AwDys (4 males) took part in this study as well. The fresh participants were those who recently signed up to take part in prospective studies conducted at Aston University. All control participants had normal or corrected-to-normal visual acuity. With the exception of 3 female AwDys having diagnosed with dyslexia in childhood, the remaining 13 AwDys received a formal diagnosis in adulthood by a qualified psychologist. Two control participants were left-handed, whilst the rest of the participants were right-handed. 4 controls and 2 AwDys were bilinguals, whilst the rest of the participants were native English speakers. This study was conducted solely on its own, with tests conducted at two separate sessions (psychometric screening and experimentation) lasting roughly 1 – 1.5 hours for each participant. A monetary reward of £10 was offered upon completion of the study.

3.4.2 Preliminary Screening

- Ethics - The current study was approved by the Department of Psychology Ethics Committee (Aston University). Initially, all participants were subjected to a short oral debriefing session which described the main procedures so that they knew what to expect in this particular research study. Following the completion of the study, all participants were offered a printed hardcopy summarising the debrief session.
- Risk Assessment - Risk assessments were conducted similarly to that in study 1 (see **section 2.4.2.2**).
- Informed Consent - All participants were required to provide an informed consent similar to that in study 1 (see **section 2.4.2.2**).

3.4.3 Standardised Screening Tests

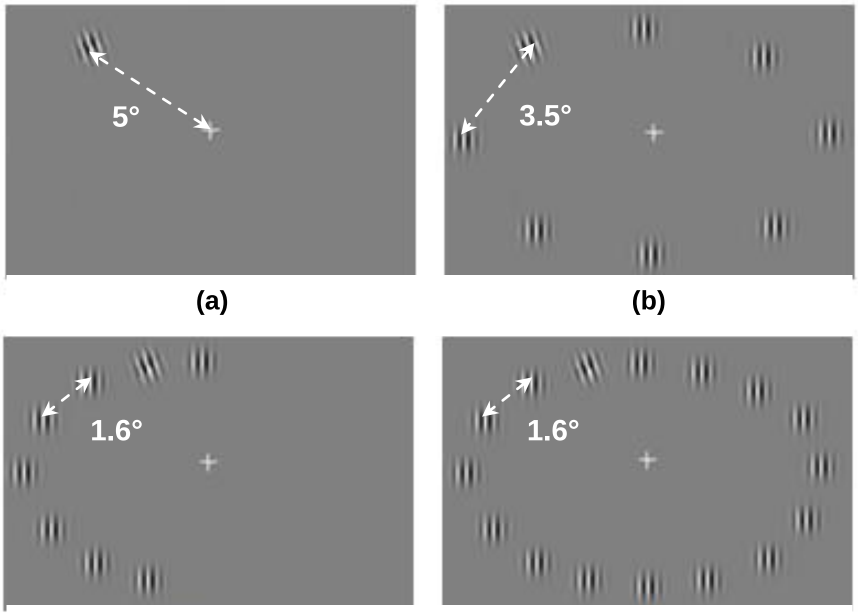
All three assessments, namely WIAT – II Spelling, WIAT – II Word Reading, and IQ (Full scale) were carried out similarly to that in study 1 (see **section 2.4.3**). The psychometric details of these measures for both groups are summarized in **Table 2**.

3.4.4 Apparatus, Experimental Stimuli and Cues

- This study utilized the exact piece of apparatus and corresponding specifications similar to that in study 1.
- The stimuli (both target and distracting Gabor patches) employed were identical to study 1 in terms of its size, luminance, orientation, etc (see **sections 2.4.4 – 2.4.6**).

3.4.5 Set-size Configuration and Spacing

In this study, set-sizes 1, 8 and 16 were used to exert varying task demands (**figure 23**). The Gabor patches were positioned on the circumference of an imaginary circle (5° from the fixation point) at a minimum of one (**figure 23a**) and a maximum of sixteen (**figure 23d**) positions. In between both these extremes, set-size 8 was of two forms, namely spread (**figure 23b**) and crowded (**figure 23c**), both of which had the same configuration as that in study 1. The spacing between adjacent Gabor patches (target-distractor and distractor-distractor) was restricted dependent on the set-size, 3.5° visual angle between each stimuli for the spread condition (set-size-1 and 8-spread) reducing down to 1.6° in the crowded condition (set-size-8 and 16-crowded).



(a) (b)

(c) (d)

Figure 23: Stimulus set-sizes and spacing patterns (**a**) 1-spread (**b**) 8-spread (**c**) 8-crowded and (**d**) 16-crowded. Note the changes in spacing between Gabor's among each set-size. As set-size increases, there is a corresponding increased crowding effect. PS: In each set-size, there is only 1 tilted target with the rest being distractors.

3.4.6 Study Design

3.4.6.1 Variables of Interest

Participants were required to indicate the orientation of the tilted target stimuli during a two alternative forced choice task. The probability at which these target stimuli appeared tilted either to the left or right was equally probable with each tilt associated with a given degree of difficulty. These were present in each of the four set-size configurations which occurred 25% of the time during the entire trial sequence. Each cue appeared for one third of the trials. All in all, three independent variables gave rise to a total of 24 stimulus conditions of interest respectively, i.e.

- Cue type (pre-cue, no-cue and post-cue) = 3
- Set-size (1, 8-spread, 8-crowded and 16-crowded) = 4
- Difficulty (easy, i.e. -5°/+5°; and Hard, i.e. -2°/+2°) = 2

For both the practice and the main experiments, the target stimuli as well as the order of conditions were varied randomly for all the participants.

3.4.6.2 Calibration of Stimulus Display

The stimulus display duration (300 msec by default[14]) was tuned to each participant's level of response accuracy during the initial practice and calibration session ahead of the main experiment. In any block of 24 short practice trials (2 trials for each condition), a reduction 10 msec occurred when overall response accuracy surpassed 90% and the opposite was true when the overall response accuracy fell beyond 60%[15]. This method of calibrating the response accuracy to the stimulus display duration therefore ensured there was no saturation in performance. This maintained the participants overall performance accuracy between 60% - 90%[16]. Furthermore, the short working range of the stimulus display (110 msec by default ±10 msec) prevented any scanning eye movements during the visual search process.

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[14] Compared to controls, AwDys generally took far too many practice trials to get to grips with the speed of stimulus presentation in study 1. By extending the duration slightly longer to 300 msec, we expected that this would allow participants to tune well with the speed of stimulus presentation.

[15] Despite setting the floor threshold to 50% in Study 1, the findings in some cases showed detection accuracies closer to 50% (especially with some AwDys). Having spared more time by increasing the stimulus display duration, we expected the overall performance to improve. Hence we raised the floor threshold to 60% for better approximation of the performance differences.

[16] The average display durations of the AwDys and the control group differed significantly [264 msec vs. 246 msec, $t(29) = 4.624$, $p < .001$].

3.4.7 Procedure

3.4.7.1 The Experiment

Figure 24 illustrates the sequences that took place in a single trial. Each trial sequence commenced with a blank gray screen with a central fixation point (110 msec) initiated by a key-press. The participants were instructed to fixate their eyes at this position right throughout the experiment.

Each trial sequence varied according to one of three random cues. In one-third of the trials, following the initial fixation, the cue display consisting of a pre-cue lasting 80 msec (i.e. 50 msec cue-ON[17] and 30 msec cue-OFF) was presented. At the very same juncture, a blank fixation display was presented (80 msec) in the remainder of trials (signifying an un-cued display). Immediately after this interval, a stimulus display (consisting either set-size 1, 8-spread, 8-crowded or 16-crowded) was presented for a variable duration (based on an individual's level of accuracy), followed by a post-cue (80 msec, in one-third of the trials) or an un-cued blank fixation display (80 msec, in one-third of the trials). Both the pre and post-cues were either 100% valid (peripherally presented informative cue which indicated the precise location of the upcoming target within the sixteen probable locations) or neutral (centrally located uninformative cue) in nature. The un-cued displays were generally controlled conditions which did not provide any information regarding the location of the target stimuli. Before completion of each trial, participants were required to input their response to indicate if the orientation of the target (compared to the perfectly vertical distractors) Gabor patch was to the left (by key-pressing "Z") or to the right (by key-pressing "M"). Following the presentation of each search array, the stimuli appeared unmasked. However, with the help of the practice session(s), each participant came to terms with the fact that even though there was no masking as such, during the response phase they were required to respond within 3000 msec. Failing to do so brought up a response reminder screen requesting an input response for the target stimuli already presented. This reminder screen acted as an early pre-mask for the follow up trial immediately after the participant response. Having this at the back of the participants mind, it ensured that the participants responded not just accurately but also quickly thereby enabling to minimize any response bias.

In total, fifteen blocks of 48 trials each were run for the main experiment, requiring roughly 20 – 25 minutes in total for each participant.

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[17] By having the cue display on for 30 msec in study 1, it was though that this time duration could have been actually too quick for AwDys to detect the cue with ease. This was the reason for extending the duration slightly longer to 50 msec.

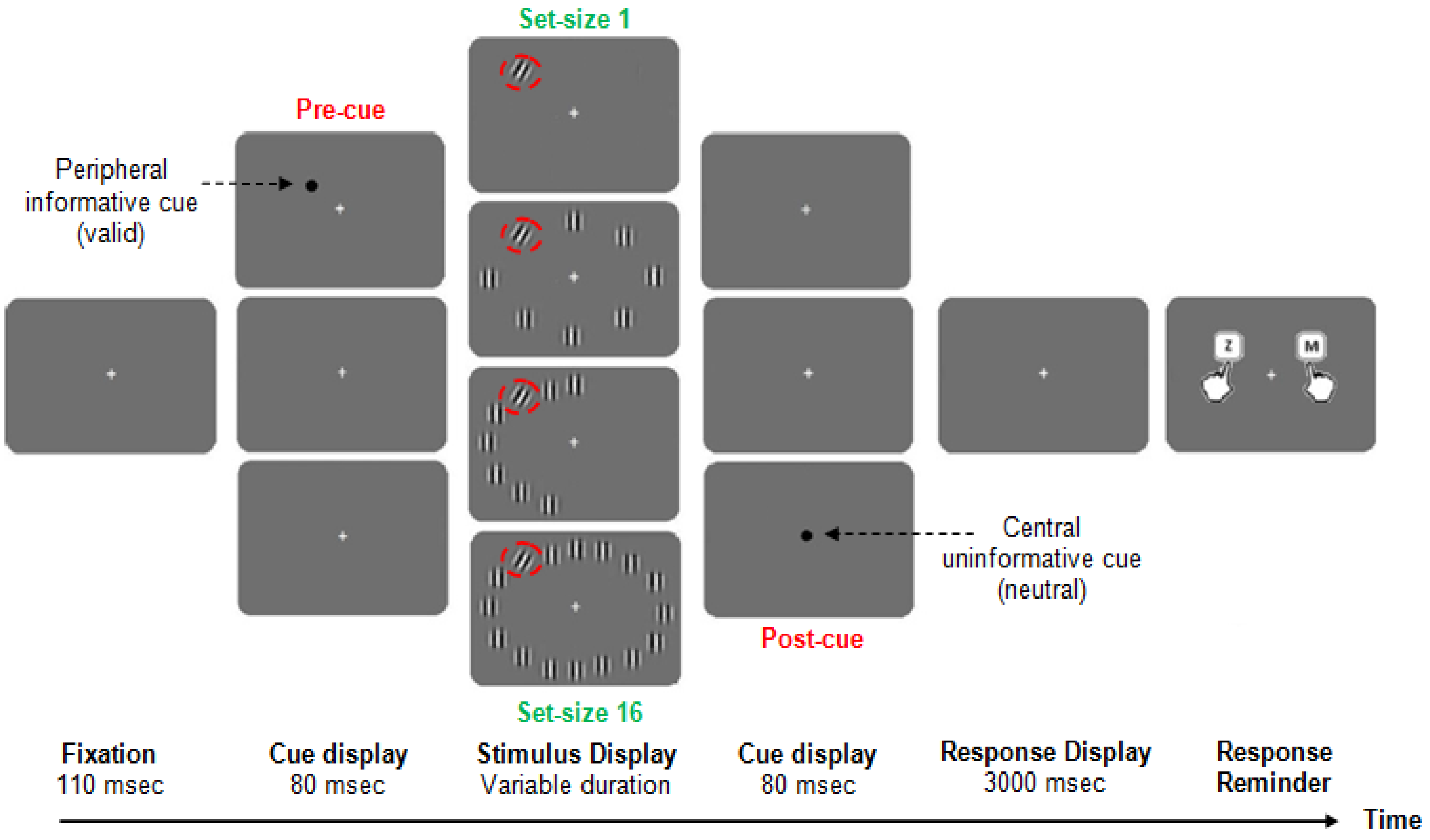


Figure 24: Schematic sequence of the visual search experiment in Study 2. Each trial had ONLY 1 of 3 cueing conditions: (a) **pre-cue** which indicated the precise location of the upcoming target, (b) **post-cue** which indicated the precise target location of the already presented stimulus containing the target, and (c) an **un-cued** display. The pre and post-cues were either valid (presented peripherally) or neutral (presented at fixation). The set-size 8 stimulus display was either spread or crowded. For the sake of simplicity, the target shown in the stimulus display is tilted to the right (as indicated by the dotted red circle).

3.4.7.2 Statistical Analysis

One-way mixed design ANOVA in SPSS (version 14.0) were used to quantify if both groups differed in age, IQ, WIAT–II spelling or word reading ability. These measures were further analysed using an independent samples t-test (equal variances not assumed, with 2-tailed significance levels). Mean percentage response accuracy data from the spatial cueing task were analysed using a three-factor ANOVA. The between participant factor was group (controls and AwDys) whilst the three within-participant factors were cue type (pre, post and no-cue), display type (1 stimulus, 8 stimuli-spaced, 8 and 16 stimuli-crowded) and task difficulty (easy and hard). Incorrect responses were excluded from the analysis. Main effects were analysed prior to individual/group effects. Pearson correlations were computed in order to explore correlations between spacing and set-size, with that of IQ, standardised spelling and reading scores. Spacing and set-size measures were indexed by the difference in percentage accuracy between valid (pre and post-cues) and neutral cue conditions for targets with the easy tilt.

3.5 Results

3.5.1 Psychometric Assessment

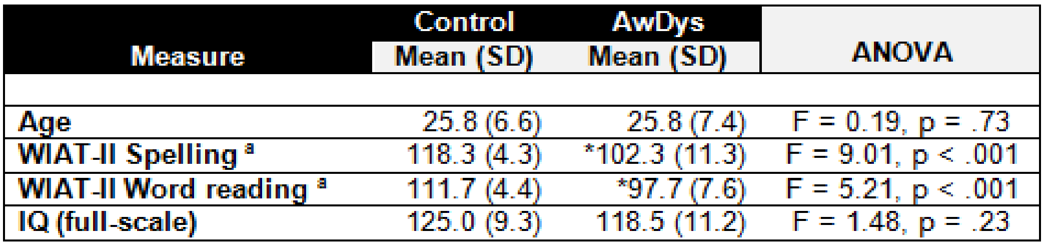
Following psychological screening, one control and one AwDys[18] were excluded, with both groups being closely matched for age (controls: M = 25.8, SD = 6.6, AwDys: M = 25.8, SD = 7.4) $F_{(1, 29)} = 0.19$, MSE = 2.83, $p = .73$, $\eta_p^2 = .02$, and IQ (controls: M = 125.0, SD = 9.3, AwDys: M = 118.5, SD = 11.2) $F_{(1, 29)} = 1.48$, MSE = 8.42, $p = .23$, $\eta_p^2 = .10$. Compared to controls, AwDys showed a significant discrepancy in the standard score units for WIAT-II spelling (controls: M = 118.3, SD = 4.3; AwDys: M = 102.3, SD = 11.3) $F_{(1, 29)} = 9.01$, MSE = 26.47, $p < .001$, $\eta_p^2 = .69$ and word reading (controls: M = 111.7, SD = 4.4; AwDys: M = 97.7, SD = 7.6) $F_{(1, 29)} = 5.21$, MSE = 21.25, $p < .001$, $\eta_p^2 = .78$. The summary statistics of the analysed screened data are presented in **Table 2**.

The exclusion criteria from the AwDys group meant that a mean reading score at least 2 *SD* below the mean age level was required. On some occasions, controls exhibited a significantly poor performance on either spelling or reading. This happened as WIAT-II test hits the ceiling for age. Nevertheless, participants with an IQ below 85 were excluded in all cases.

[18] Both these individuals reading scores were well and truly below the cut-off score, failing to meet the IQ selection criterion.

Table 2: Demographic and psychometric group characteristics for Study 2. Data from a total of 16 controls and 15 AwDys data were utilized. Based on the statistics (mean scores, standard deviations and ANOVA results), findings demonstrated significantly poor literacy skills and IQ (full-scale) in AwDys compared to the control group.

[a] The composite standard scores (SS) predicted from IQ tests fell in range with the population mean ($M_{SS} = 100$, $SD_{SS} = 14$, and percentile rank = 50).



Measure	Control Mean (SD)	AwDys Mean (SD)	ANOVA
Age	25.8 (6.6)	25.8 (7.4)	F = 0.19, p = .73
WIAT-II Spelling [a]	118.3 (4.3)	*102.3 (11.3)	F = 9.01, p < .001
WIAT-II Word reading [a]	111.7 (4.4)	*97.7 (7.6)	F = 5.21, p < .001
IQ (full-scale)	125.0 (9.3)	118.5 (11.2)	F = 1.48, p = .23

3.5.2 Difference in Cued Visual Search

To re-cap, this study provided the opportunity to make use of display types 1 and 16, in addition to display type 8 spacing manipulation to study the effects of cueing, set-size, stimulus spacing and task difficulty on performance of both controls and AwDys. Before analysing individual effects based on a given condition(s), the following overall main effects provide a summary of what the observed patterns might look like in the analysis to follow.

A four-factor ANOVA of search performance was carried out in a group wise manner with cue type (pre, post and no-cue), display type (set-sizes 1, 8-spread, and 16), and task difficulty (easy and hard) as repeated factors. Results showed a significant main effect of cue type ($F_{(2, 58)} = 30.93$, MSE = 0.010, $p < .001$, $\eta_p^2 = .51$), display type ($F_{(2, 58)} = 128.48$, MSE = 0.015, $p < .001$, $\eta_p^2 = .81$) and task difficulty ($F_{(1, 29)} = 80.33$, MSE = 0.008, $p < .001$, $\eta_p^2 = .73$). Furthermore, there were significant main effects of group shown by interactions between cue type by group ($F_{(2, 58)} = 11.54$, MSE = 0.010, $p < .001$, $\eta_p^2 = .28$); display type by group ($F_{(2, 58)} = 36.23$, MSE = 0.015, $p < .001$, $\eta_p^2 = .55$); and task difficulty by group ($F_{(1, 29)} = 21.89$, MSE = 0.008, $p < .001$, $\eta_p^2 = .42$). Despite attempts to equate overall performance, controls showed a higher performance than AwDys ($F_{(1, 29)} = 50.32$, MSE = 0.029, $p < .001$, $\eta_p^2 = .61$). These group variations indicate that the performance of AwDys and controls differed selectively based on all three variables in question. This suggests a possibility for higher search performance in noise-reduced displays, especially when stimuli were cued, and when the orientation of stimuli was easier to discriminate.

The analysis to follow is divided into the following 4 sections investigating: (i) cueing effects in general, i.e. set-size 1 and 16, (ii) spacing effects, i.e. set-size 8-spread and 8-crowded, (iii) set-size effects, i.e. set-size 8-crowded and 16, and (iv) the relationship of the above three measures (i.e. cueing, spacing and set-size) with the obtained WIAT-II reading and spelling scores.

3.5.3 Effect of Cueing on Visual Search

This section sets out to investigate how well the individual cue types assisted both groups only in display types 1 and 16 during the visual search process. We chose both these display types to portray different noise levels, with least noise present at set-size 1 and the highest at set-size 16.

3.5.3.1 Extent of Pre-cue Use (Signal Enhancement and Noise Exclusion)

A four-factor ANOVA of search performance was carried out with group (controls, AwDys), cue type (pre and no-cue), display type (set-sizes 1 and 16) and difficulty (easy and hard) as repeated factors. Findings showed a significant main effect of group ($F_{(1, 29)} = 41.5$, $p < .001$, MSE = 0.020, $\eta_p^2 = .58$), display type ($F_{(1, 29)} = 172.9$, MSE = 0.012, $p < .001$, $\eta_p^2 = .85$), cue type ($F_{(1, 29)} = 50.66$, MSE = 0.009, $p < .001$, $\eta_p^2 = .63$), and task difficulty ($F_{(1, 29)} = 51.9$, MSE = 0.004, $p < .001$, $\eta_p^2 = .65$). Similarly, there were significant two-way group interactions with cue type ($F_{(1, 29)} = 16.4$, MSE = 0.011, $p < .001$, $\eta_p^2 = .43$), display type ($F_{(1, 29)} = 50.66$, MSE = 0.017, $p < .001$, $\eta_p^2 = .51$), and task difficulty ($F_{(1, 29)} = 51.9$, MSE = 0.004, $p < .001$, $\eta_p^2 = .55$). Also, significant three-way group interactions were present between display type and task difficulty ($F_{(1, 29)} = 19.21$, MSE = 0.005, $p < .001$, $\eta_p^2 = .38$), and display type and cue type ($F_{(1, 29)} = 10.73$, MSE = 0.008, $p = 0.003$, $\eta_p^2 = .25$). The four-way group interaction between display type, cue type and task difficulty failed to reach significance ($F_{(1, 29)} = 1.50$, MSE = 0.006, $p = .229$, $\eta_p^2 = .04$).

The pattern of pre-cue use was then measured using a three-factor ANOVA [with group (controls, AwDys), cue type (pre and no-cue), and task difficulty (easy and hard) as repeated factors] separately across each display type. The important effects of interest are highlighted in **figure 25**. At set-size 1, the effects of cueing ($F_{(1, 15)} = 0.002$, MSE = 0.003, $p = .96$, $\eta_p^2 = .00$), task difficulty ($F_{(1, 15)} = 0.007$, MSE = 0.003, $p = .93$, $\eta_p^2 = .00$), and the cueing by task difficulty interaction ($F_{(1, 15)} = 0.30$, MSE = 0.004, $p = .59$, $\eta_p^2 = .02$) failed to reach significance in controls. For AwDys, the effect of cueing reached significance ($F_{(1, 14)} = 14.96$, MSE = 0.003, $p < .001$, $\eta_p^2 = .48$), unlike the effect of task difficulty ($F_{(1,\ 14)} = 1.39$, MSE = 0.005, $p = .06$, $\eta_p^2 = .18$), and the cue type by task difficulty interaction ($F_{(1,\ 14)} = 1.68$, MSE = 0.003, $p = .21$, $\eta_p^2 = .10$). At set-size 16, controls showed a significant cueing effect ($F_{(1,\ 15)} = 9.14$, MSE = 0.014, $p < 0.05$, $\eta_p^2 = .36$), much lower compared to that shown by AwDys ($F_{(1,\ 14)} = 35.9$, MSE = 0.120, $p < .001$, $\eta_p^2 = .82$). Importantly, a cue by task difficulty interaction was significant at set-size 16 in AwDys ($F_{(1,\ 14)} = 71.1$, MSE = 0.007, $p < .05$, $\eta_p^2 = .38$) unlike that in controls ($F_{(1,\ 15)} = 0.38$, MSE = 0.003, $p = .55$, $\eta_p^2 = .02$).

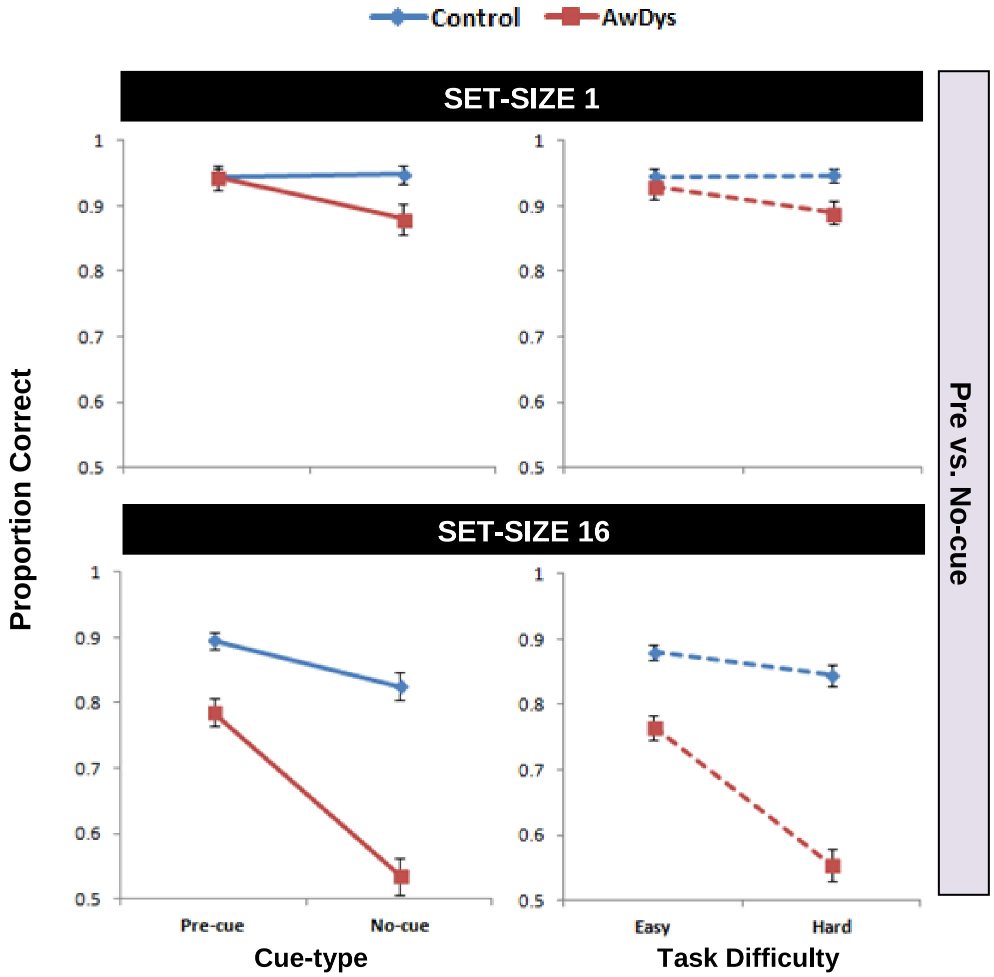


Figure 25: Effect of pre-cueing on group performance as a function of **(left)** set-size and **(right)** task difficulty. In AwDys, the largest change in performance occurs at set size 16 as the task gets predominantly hard compared to a very small change in performance regardless of task difficulty at the lowest set-size. Error bars represent ±1 standard error of the mean percentage response accuracy.

Taken together, these results suggest that due to the presence of no external noise at the lowest of set-sizes, both groups were pretty much able to enhance the signal at ease with or marginally without the use of pre-cues. However, given the higher noise involved at the largest set-size, AwDys were still able to both enhance the signal and exclude the noise much to the advantage of the pre-cue presented to them. The drop in performance of AwDys in the no-cue condition meant that they were not able to cope with the increased task demands as the task discrimination became harder at higher noise. Despite this, even when the task was easy, especially at low noise levels (set-size 1), performance in both groups did not reach a 100% maximum and it suspected that this could be due to the presence of internal decisional noise (as a result of the "location uncertainty").

3.5.3.2 Extent of Post-cue Use (Noise Exclusion)

A four-factor ANOVA of search performance was carried out with group (controls, AwDys), cue type (post and no-cue), display type (set-sizes 1 and 16), and task difficulty (easy and hard) as repeated factors. The important effects of interest are highlighted in **figure 26**. Main effects of group ($F_{(1, 29)} = 81.4$, MSE = 0.024, $p < .001$, $\eta_p^2 = .73$), display type ($F_{(1, 29)} = 20.8$, MSE = 0.053, $p < .001$, $\eta_p^2 = .88$), and task difficulty ($F_{(1, 29)} = 27.1$, MSE = 0.006, $p < .001$, $\eta_p^2 = .48$) were all significant except for cue type ($F_{(1, 29)} = 3.55$, MSE = 0.013, $p = .068$, $\eta_p^2 = .09$). There were significant two-way group interactions with display type ($F_{(1, 29)} = 26.0$, MSE = 0.028, $p < .001$, $\eta_p^2 = .65$), cue type ($F_{(1, 29)} = 16.7$, MSE = 0.011, $p < 0.05$, $\eta_p^2 = .25$), and task difficulty ($F_{(1, 29)} = 7.5$, MSE = 0.005, $p < 0.05$, $\eta_p^2 = .20$). Also, significant three-way group interactions were present between display type and task difficulty ($F_{(1, 29)} = 6.71$, MSE = 0.006, $p < 0.05$, $\eta_p^2 = .18$), in addition to a four-way group interaction between display type, cue type and task difficulty ($F_{(1, 29)} = 8.39$, MSE = 0.003, $p < 0.05$, $\eta_p^2 = .29$).

Given this significant four-way interaction, the pattern of post-cue use was then measured using a three-way ANOVA [with group (controls, AwDys), cue type (post and no-cue), and task difficulty (easy and hard) as repeated factors] separately across each display type and group.

When comparing across display types, controls showed a significant effect of cue type ($F_{(1, 15)} = 27.2$, MSE = 0.011, $p = .004$, $\eta_p^2 = .26$) at set-size 16 unlike that at set-size 1 ($F_{(1, 15)} = 1.66$, MSE = 0.026, $p = .171$, $\eta_p^2 = .08$). However, the effect of cueing in AwDys was only significant at set-size 1 ($F_{(1, 14)} = 34.6$, MSE = 0.002, $p = .006$, $\eta_p^2 = .25$) unlike at set-size 16 ($F_{(1, 14)} = 4.36$, MSE = 0.016, $p = .094$, $\eta_p^2 = .02$). AwDys showed a significant effect of task difficulty at set-size 16 ($F_{(1, 14)} = 20.0$, MSE = 0.007, $p < .001$, $\eta_p^2 = .59$) but not at set-size 1 ($F_{(1, 14)} = 1.29$, MSE = 0.017, $p = .081$, $\eta_p^2 = .11$), an effect which failed to reach significance for controls at both set-sizes.

When comparing across groups, a significant two-way interaction between cue type and task difficulty emerged for controls (F $_{(1,\ 15)}$ = 34.23, MSE = 0.017, p < .001, η_p^2 = .54), whilst for AwDys a significant display type by task difficulty interaction became evident (F $_{(1,\ 14)}$ = 25.10, MSE = 0.006, p = 0.014, η_p^2 = .31).

Taken together, these results suggest a set-size dependent usage of post-cues in both groups. When the nose was at its lowest, AwDys utilized the post-cue unlike controls. However, when the noise was at its peak, while controls utilized the post-cue to their advantage, AwDys did not use post-cues successfully at all. This is based on the largest drop in performance of AwDys from almost ceiling performance at set-size 1 to almost floor performance at set-size 16. In addition, AwDys did not use the post-cues to the same extent as they did with pre-cues, with the performance of the former similar to that when un-cued.

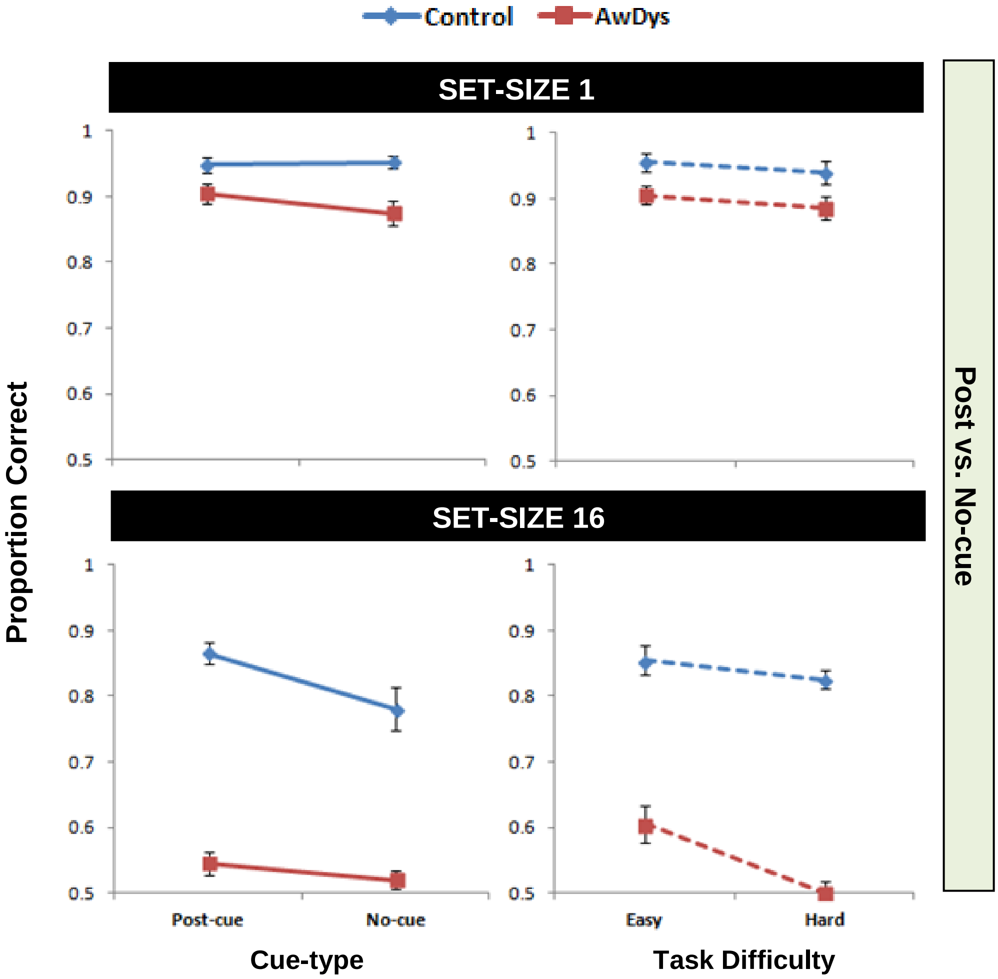


Figure 26: Effect of post-cueing on group performance as a function of **(left)** set-size and **(right)** task difficulty. Unlike controls, in AwDys, performance drops significantly at set-size 16 regardless of the display being cued or not. Error bars represent ±1 standard error of the mean percentage response accuracy.

3.5.4 Effect of Spacing

With both groups utilising each cue differently at different set-sizes, the next aim was to investigate how these cues were being utilized under different spacing conditions whilst set-size remained constant. The extent of crowdedness was varied under two different forms of spacing conditions, the stimuli was either widely spaced (3.5° - set-size 8-spread) or narrowly spaced (1.6° - set-size 8-crowded) when presented on the stimulus display, with set-size remaining constant.

3.5.4.1 Main Effects

A four-factor ANOVA of search performance was carried out with cue type (pre, post and no-cue), display type (8-spread and 8-crowded) and task difficulty (easy and hard) as repeated factors. Despite attempts to equate overall performance, a significant main effect of group ($F_{(1,\ 29)} = 12.9$, MSE = 0.043, $p < .001$, $\eta_p^2 = .30$) was observed with better performance observed in control participants'. As expected, a significant main effect of display type ($F_{(1,\ 29)} = 46.5$, MSE = 0.011, $p < .001$, $\eta_p^2 = .61$), cue type ($F_{(1,\ 29)} = 10.4$, MSE = 0.009, $p < .001$, $\eta_p^2 = .26$) and task difficulty ($F_{(1,\ 29)} = 12.7$, MSE = 0.008, $p < .001$, $\eta_p^2 = .30$) was found. A significant two-way interaction also became evident between display type and cue type ($F_{(2,\ 58)} = 6.2$, MSE = 0.011, $p = .004$, $\eta_p^2 = .17$) alongside a significant two-way group interaction with display type ($F_{(1,\ 29)} = 17.2$, MSE = 0.015, $p < .001$, $\eta_p^2 = .37$). The four-way group interaction between display type, cue type and task difficulty reached significance ($F_{(2,\ 58)} = 5.2$, MSE = 0.003, $p = .007$, $\eta_p^2 = .15$). None of the other effects or interactions reached statistical significance. These results suggest that AwDys despite being prone to reduced search performances in crowded displays were still able to perform better in spread displays especially when the search array was pre-cued under easy conditions (predicted from the outcome of study 1).

3.5.4.2 Spacing Effect with respect to each Group

With the primarily interest being the effect of pre and post-cues on display type, post-hoc analyses were conducted separately for pre, post and un-cued conditions using a two-way ANOVA with spacing (8-spread and 8-crowded) and task difficulty (easy and hard) as repeated factors. On one hand, when the stimulus display was pre-cued (**figure 27 – top horizontal panel**), AwDys showed no significant effect of spacing ($F_{(1,\ 14)} = 0.24$, MSE = 0.012, $p = .633$, $\eta_p^2 = .06$) similar to controls ($F_{(1,\ 15)} = 0.40$, MSE = 0.009, $p = .536$, $\eta_p^2 = .04$). Neither group showed any significant effects of task difficulty even though the AwDys

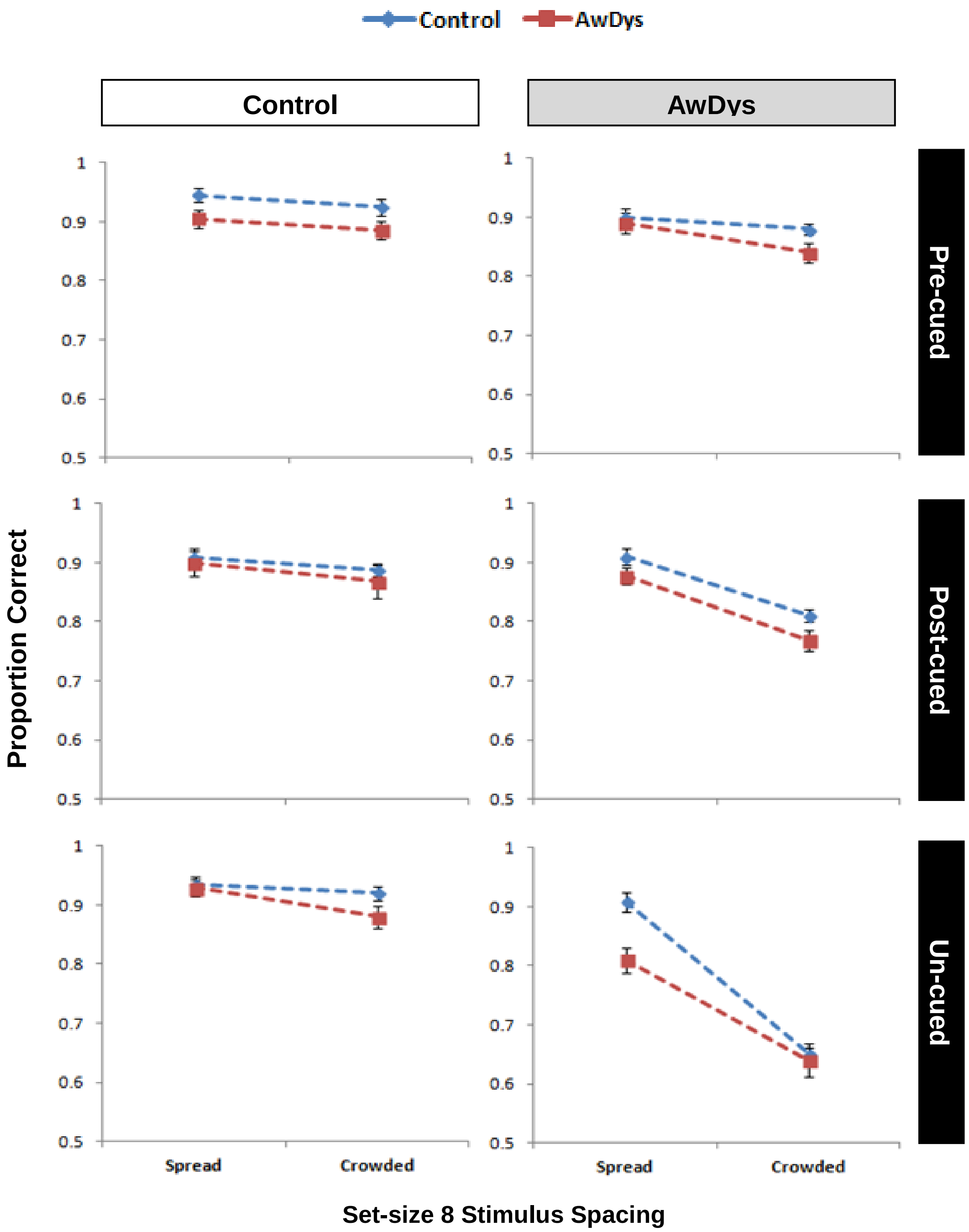


Figure 27: Spacing effects as a function of cueing and task difficulty. In AwDys, performance drops significantly at crowded conditions when the stimulus display is un-cued regardless of task difficulty. Error bars represent ±1 standard error of the mean percentage response accuracy.

narrowly missed significance ($F_{(1,\ 14)}$ = 4.7, MSE = 0.007, p = .061, η_p^2 = .11). Similarly, both groups did not show a spacing by task difficulty interaction (control: $F_{(1,\ 15)}$ = 0.56, MSE = 0.003, p = .464, η_p^2 = .05; AwDys: $F_{(1,\ 14)}$ = 0.07, MSE = 0.003, p = .799, η_p^2 = .02), demonstrating that the pattern of performance for both groups was similar when the target stimuli was pre-cued. On the other hand, when the stimulus display was post-cued (**figure**

27 – central horizontal panel), AwDys did have a significant effect of spacing ($F_{(1, 14)} = 53.17$, MSE = 0.007, $p < .001$, $\eta_p^2 = .57$) compared to controls who lacked a spacing effect all together ($F_{(1, 15)} = 1.40$, MSE = 0.008, $p = .253$, $\eta_p^2 = .08$). None of the other effects or interactions reached any significance. Both these findings shows that although pre-cues enabled AwDys to overcome the crowding effect, the post-cue did not confer to any advantage what-so-ever.

However, when un-cued (**figure 27 – bottom horizontal panel**), controls showed no significant effect of spacing ($F_{(1, 15)} = 2.8$, MSE = 0.012, $p = .109$, $\eta_p^2 = .15$), unlike AwDys ($F_{(1, 14)} = 26.5$, MSE = 0.017, $p < .001$, $\eta_p^2 = .65$). AwDys also showed a significant effect of task difficulty ($F_{(1, 14)} = 5.9$, MSE = 0.011, $p = .015$, $\eta_p^2 = .29$), and a two-way interaction between spacing and task difficulty ($F_{(1, 14)} = 10.8$, MSE = 0.004, $p = .006$, $\eta_p^2 = .44$) unlike in the control group [task difficulty ($F_{(1, 15)} = 1.66$, MSE = 0.007, $p = .216$, $\eta_p^2 = .09$); spacing and task difficulty ($F_{(1, 15)} = 1.23$, MSE = 0.002, $p = .154$, $\eta_p^2 = .12$) respectively].

Taken together, these findings suggest that AwDys demonstrate a bigger effect of spacing when the stimulus display is un-cued, second to it being post-cued. Furthermore, given the easy conditions when post and un-cued, performance still dropped significantly when the search array was crowded, which goes to show a lesser impact of task difficulty on search performance in AwDys. These findings clearly indicate two important outcomes; (i) the AwDys were solely dependent on the (informative) pre-cue to modulate their attention in successfully overcoming the crowding effect, (ii) with the effect of crowding especially in an un-cued display made target detection significantly harder for AwDys.

3.5.5 Effect of Set-size

Having investigated the effect of spacing on search performance (with similar outcomes observed in studies 1 and 2), the following section examines the set-size effects in more detail. It is evident that increasing spacing had a significant effect on search performance in AwDys as well as the advantage they gained from cueing (faltered more when post-cued unlike when pre-cued). However, the question remains as to what happens when set-size increases while spacing remains constant. For this reason, set-sizes 8-crowded and 16 were utilized for the purposes of analysis given the common inter-stimulus-spacing (1.6° by visual angle), unlike in set-sizes 1 and 8-spread. Hence, the outcome from the following batch of analysis excluded a potential crowding effect.

3.5.5.1 Attention Orientation

The main effects were analysed using a three-factor ANOVA with set-size (8-crowded and 16), cue type (pre, post and no-cue) and task difficulty (easy and hard) as repeated factors, separately for each group. The important effects of interest are highlighted in **figure 28**. The results for the control group showed a significant effect of task difficulty ($F_{(1, 15)} = 7.8$, MSE = 0.007, p = .013, $\eta_p^2 = .33$), and cue type ($F_{(2, 28)} = 3.9$, MSE = 0.020, p = .029, $\eta_p^2 = .20$), except for set-size which narrowly missed significance ($F_{(1, 15)} = 4.6$, MSE = 0.018, p = .057, $\eta_p^2 = .22$). None of the other interactions such as set-size and cue-type ($F_{(2, 28)} = 8.01$, MSE = 0.008, p = .46, $\eta_p^2 = .05$), set-size and task difficulty ($F_{(1, 15)} = 0.07$, MSE = 0.005, p = .79, $\eta_p^2 = .03$), and set-size, cue type and task difficulty ($F_{(2, 32)} = 0.34$, MSE = 0.003, p = .72, $\eta_p^2 = .02$) were of any statistical significance. A pair-wise comparison for cue type indicated a significant difference between pre and un-cued (p = 0.011) conditions.

In contrast, AwDys showed a significant effect in set-size ($F_{(1, 14)} = 36.5$, MSE = 0.030, p < .001, $\eta_p^2 = .72$), task difficulty ($F_{(1, 14)} = 27.2$, MSE = 0.011, p < .001, $\eta_p^2 = .66$), and cue type ($F_{(2, 28)} = 29.3$, MSE = 0.023, p < .001, $\eta_p^2 = .68$). A significant two-way interaction between set-size and task difficulty ($F_{(1, 14)} = 70.1$, MSE = 0.004, p < .001, $\eta_p^2 = .83$), in addition to a three-way interaction between set-size, task difficulty and cue type ($F_{(2, 28)} = 8.58$, MSE = 0.006, p = .010, $\eta_p^2 = .22$) was evident in AwDys. None of the other interactions such as set-size and cue type ($F_{(1, 28)} = 0.13$, MSE = 0.031, p = .074, $\eta_p^2 = .07$), and difficulty and cue type ($F_{(1, 28)} = 4.18$, MSE = 0.009, p = .067, $\eta_p^2 = .05$) were of any statistical significance. Based on the pair-wise comparison for cue-type, AwDys showed a pronounced significant effect between pre and post-cued (p < 0.001), and pre and un-cued (p < 0.001) conditions respectively.

3.5.5.2 Attention Focusing and Exclusion of Distractors

To elaborate further with regards to the interactions found above, a two-factor ANOVA with set-size (8-crowded and 16), and task difficulty (easy and hard) as repeated factors, was performed separately for each cue condition in a group-wise manner – see **figure 29**. This was done in order to examine whether the set-size effects varied for each group as a function of cue type.

In the pre-cued conditions, the control group demonstrated a significant effect of task difficulty ($F_{(1, 15)} = 7.30$, MSE = 0.002, p = .016, $\eta_p^2 = .31$), unlike for set-size ($F_{(1, 15)} = 0.61$, MSE = 0.015, p = .446, $\eta_p^2 = .04$), and a set-size by task difficulty interaction ($F_{(1, 15)}$

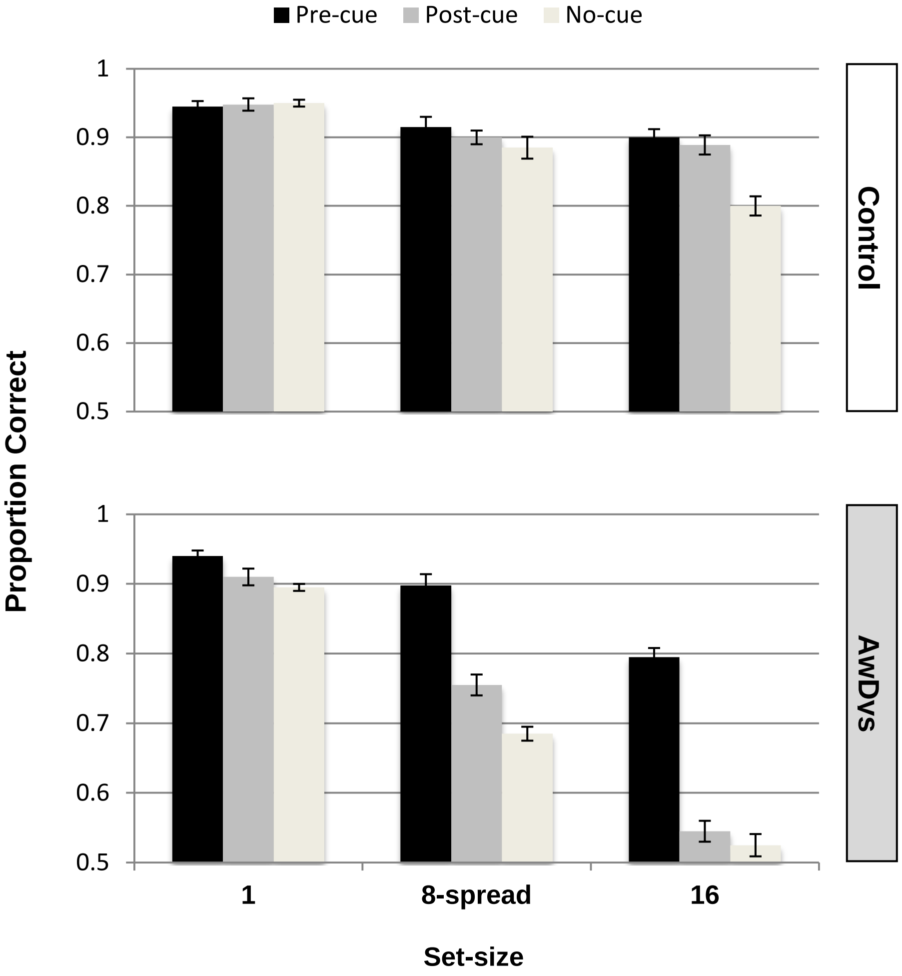


Figure 28: Set-size effects as a function of cueing for both participant groups. Error bars represent ±1 standard error of the mean percentage response accuracy.

= 0.16, MSE = 0.002, $p = .695$, $\eta_p^2 = .01$). In contrast, AwDys showed a more pronounced significant effect of set-size ($F_{(1,\ 14)} = 22.6$, MSE = 0.005, $p < .001$, $\eta_p^2 = .62$), task difficulty ($F_{(1,\ 14)} = 30.84$, MSE = 0.007, $p < .001$, $\eta_p^2 = .69$), and a set-size by task difficulty interaction ($F_{(1,\ 14)} = 20.2$, MSE = 0.008, $p < .001$, $\eta_p^2 = .59$) suggesting that the set-size effect was only apparent when the discrimination was difficult.

In the post-cued conditions, the control group showed just a significant effect of task difficulty ($F_{(1,\ 15)} = 7.14$, MSE = 0.003, $p = .017$, $\eta_p^2 = .31$) unlike for set-size ($F_{(1,\ 15)} = 1.78$, MSE = 0.007, $p = .201$, $\eta_p^2 = .10$), and a set-size by task difficulty interaction ($F_{(1,\ 15)} = 0.01$, MSE = 0.006, $p = .975$, $\eta_p^2 = .00$). In contrast, AwDys showed a significant effect of set-size ($F_{(1,\ 14)} = 17.2$, MSE = 0.024, $p < .001$, $\eta_p^2 = .55$), and task difficulty ($F_{(1,\ 14)} = 4.7$, MSE = 0.006, $p = .035$, $\eta_p^2 = .25$). The two-way interaction between set-size and task

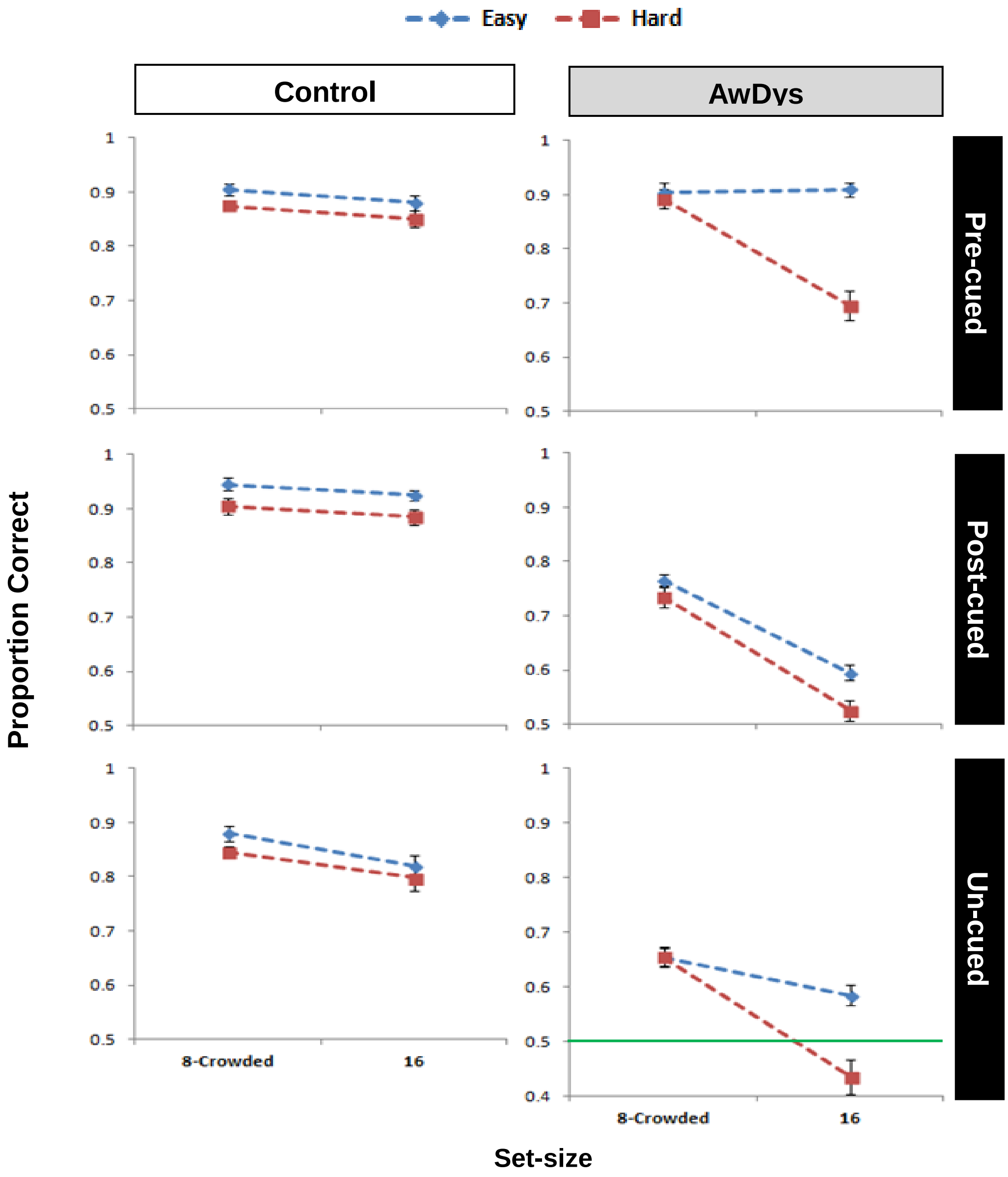


Figure 29: Set-size effects as a function of **(a)** cueing and **(b)** task difficulty. In AwDys, performance drops significantly at set size-16 in the hard condition. PS: Note the fall in performance for AwDys below the chance level (50%) as highlighted by the green line. Error bars represent ±1 standard error of the mean percentage response accuracy.

difficulty did not reach statistical significance (F $_{(1,\ 14)}$ = 0.25, MSE = 0.004, p = .624, η_p^2 = .01) this time round.

In the un-cued conditions the control group showed only a significant effect of set-size (F $_{(1,\ 15)}$ = 6.94, MSE = 0.008, p = .018, η_p^2 = .30), unlike for task difficulty (F $_{(1,\ 14)}$ = 2.45, MSE = 0.006, p = .137, η_p^2 = .13), and a set-size by task difficulty interaction (F $_{(1,\ 14)}$ = 0.55, MSE = 0.004, p = .468, η_p^2 = .03). In contrast, AwDys showed a significant effect of set-size (F $_{(1,\ 14)}$ = 16.1, MSE = 0.031, p < .001, η_p^2 = .53), task difficulty (F $_{(1,\ 14)}$ = 10.1, MSE =

0.011, $p = .008$, $\eta_p^2 = .42$), and a set-size by task difficulty interaction ($F_{(1,\ 14)} = 15.81$, $MSE = 0.006$, $p < .001$, $\eta_p^2 = .55$), the latter suggesting a larger effect of set-size when the discrimination was more difficult.

3.5.6 Relationship between Crowding, Cueing and Set-size effects with Literacy

The following section focuses on the actual literacy skills (reading, spelling, and IQ) and how well these skills were associated with the attention measures (crowding, cueing, and set-size). The potential predictive relationships were evaluated by initially creating six summary variables based on cue-type dependent participant performances from both groups across all task conditions. The easy conditions were chosen to avoid potential floor effects which were more apparent as the task became harder.

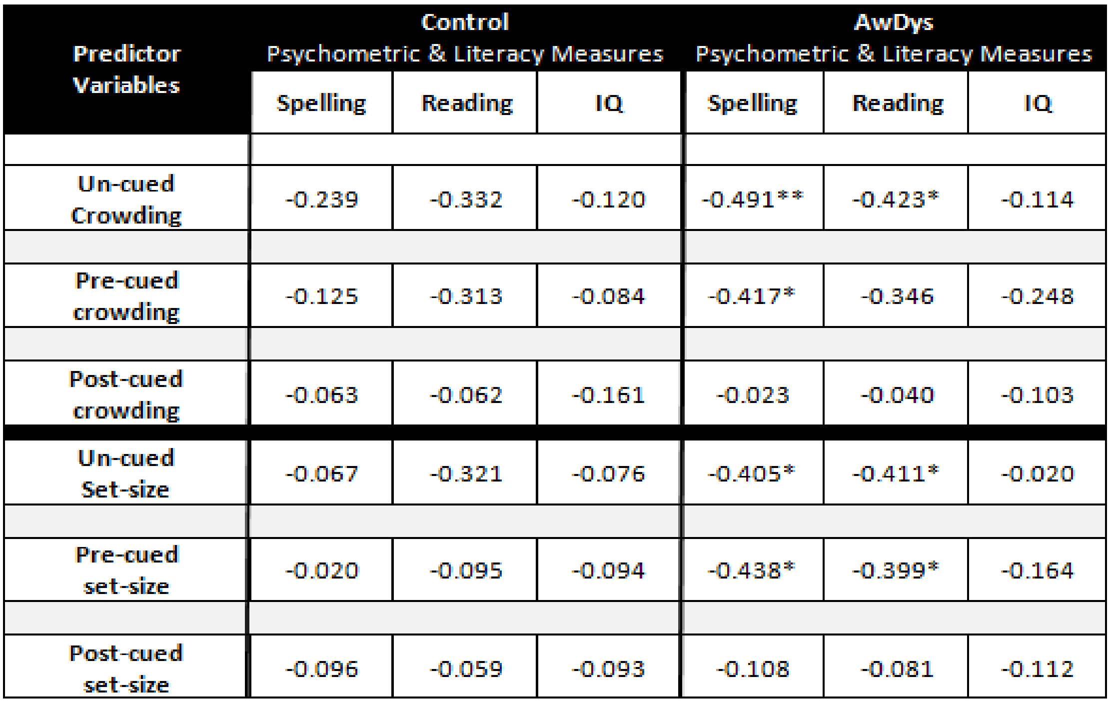
- First, the relationship between the use of both neutral (no-cue) and informative (pre and post-cues) cues across display type-8 spacing manipulation was evaluated as an operational measure of the crowding effect, independent of the number of distractors. The difference in search performance between spread and crowded display types was calculated across:
  - un-cued conditions (variable "a", i.e. *un-cued crowding effect*)
  - pre-cue vs. un-cued conditions (variable "b", i.e. *pre-cued crowding effect*)
  - post-cue vs. un-cued conditions (variable "c", i.e. *post-cued crowding effect*)

- Second, the relationship between the use of both neutral (no-cue) and informative (pre and post-cues) cues across display types 8-crowded and 16 was evaluated as an operational measure of the set-size effect. The point worth noting here is the use of data from the display type 8-crowded (rather than spread) condition so as to keep the effects of crowding constant. The difference in search performance between spread and crowded display types was calculated across:
  - un-cued conditions (variable "x", i.e. *un-cued set-size effect*)
  - pre-cue vs. un-cued conditions (variable "y", i.e. *pre-cued set-size effect*)
  - post-cue vs. un-cued conditions (variable "z", i.e. *post-cued set-size effect*)

3.5.6.1 Linear Correlation Analyses

These six summary measures of crowding, pre-cueing, post-cueing and set-size signified the predictor variables of psychometric and literacy measures. These variables pertaining to both groups were then entered separately and evaluated via correlation analyses. One potential problem when reporting correlations for both groups is the lack of homogeneity in the data sample from which a correlation is calculated, thereby not representing the true relation between the two variables of interest (e.g. Ramus et al., 2003). For this very reason, the correlations between measures were reported for each group separately (rather than across the entire sample), thereby also enabling to assess the variable(s) which are most important at influencing a particular measure. **Table 3** shows the values of Pearson's *r*.

Table 3: Correlation matrix highlighting the relationship between the effects of crowding, cueing, and set-size on measures of literacy (WIAT-II spelling and WIAT-II reading) and psychometry (IQ). Pearson's r are shown with * indicating p < .05 and ** indicating p < .001.



Predictor Variables	Control Psychometric & Literacy Measures			AwDys Psychometric & Literacy Measures		
	Spelling	**Reading**	**IQ**	**Spelling**	**Reading**	**IQ**
Un-cued Crowding	-0.239	-0.332	-0.120	-0.491**	-0.423*	-0.114
Pre-cued crowding	-0.125	-0.313	-0.084	-0.417*	-0.346	-0.248
Post-cued crowding	-0.063	-0.062	-0.161	-0.023	-0.040	-0.103
Un-cued Set-size	-0.067	-0.321	-0.076	-0.405*	-0.411*	-0.020
Pre-cued set-size	-0.020	-0.095	-0.094	-0.438*	-0.399*	-0.164
Post-cued set-size	-0.096	-0.059	-0.093	-0.108	-0.081	-0.112

As summarised in **Table 3**, controls did not show any significant correlation towards the psychometric or literacy measures, which might have been due to the smaller spread of performances, probably reflecting the achievement of a near-optimal spelling and reading strategy. The association between all six predictor variables and IQ measure for both groups were not statistically significant, suggesting that the un-cued and pre-cued effect of crowding and set-size impacted spelling and/or reading performance directly independent of general cognitive ability. AwDys showed quite a significant correlation between un-cued crowding and set-size with spelling and reading measures. **Figure 30** demonstrates these relationships further, in addition to the degree of influence caused by crowding and set-size towards each group's literacy performances. Having controlled for potential effects of IQ using a second batch of partial correlations, the findings was identical to that carried out in the first batch.

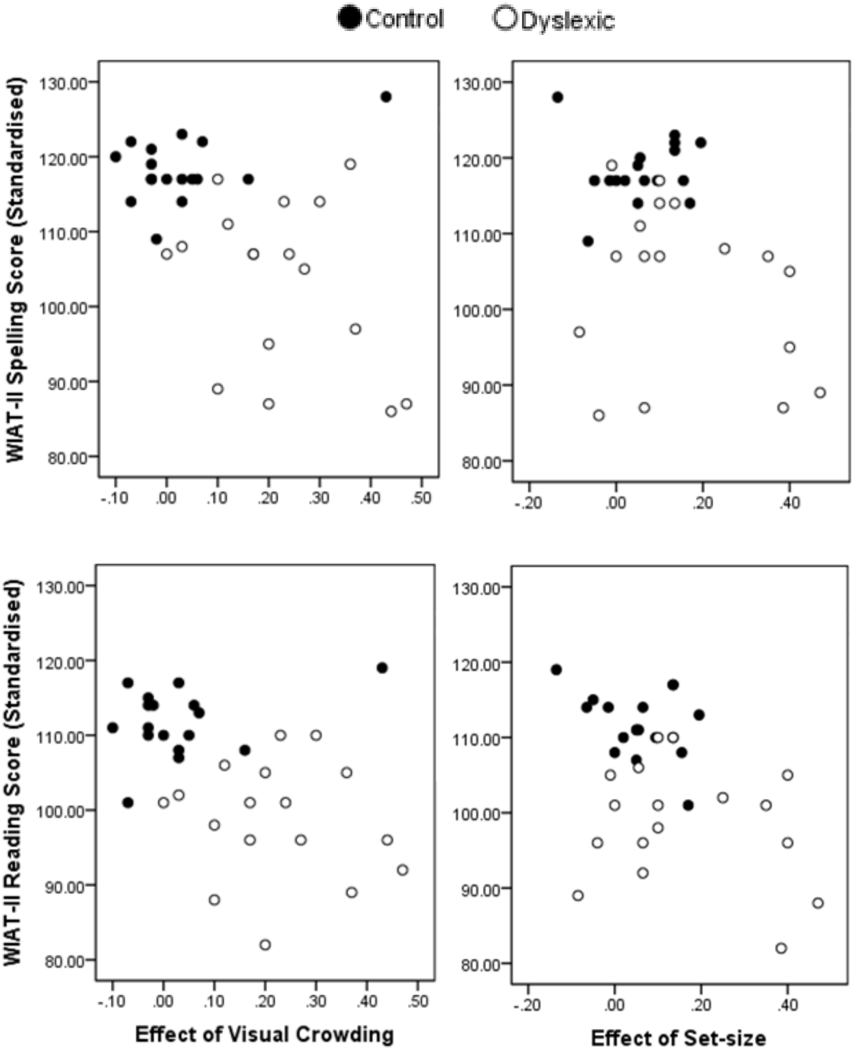


Figure 30: Scatter plots demonstrating the relationship between measures of spelling and reading achieved by both groups as a function of crowding (left panel) and set-size (right panel) effect. The effect of crowding reflects the performance difference between 8-crowded vs. 8-spread conditions, whilst that for set-size, the performance difference being set-size 8-crowded vs. sixteen conditions.

3.5.6.2 Multiple Regression Analyses

Based on the findings from **section 3.5.3.1**, variables such as crowding (un-cued), set-size (un-cued) and pre-cue use for both crowding and set-size turned out to be crucial predictors of spelling and reading ability for AwDys, unlike controls. These three measures were then entered as predictor variables of spelling and reading ability in a multiple regression analysis (on a group by group basis) to further assess the unique variance of each predictor.

When comparing these associations within different groups, the correlation confers strongly for AwDys, but not controls. For controls, although the equivalent regression analysis for spelling revealed that the predictors explained 29.4% of the variance (adjusted R^2 = .130), neither did measures of crowding [β = 0.325, t(15) = 0.305, p = .338], set-size [β = 0.147, t(15) = 0.547, p = .593], nor pre-cue use [β = 0.155, t(15) = 0.588, p = .567] turn out to be significant unique predictors. Same was true with reading whereby crowding [β = 0.279, t(15) = 1.019, p = .327], set-size [β = -0.416, t(15) = -1.530, p = .150], and pre-cueing [β = 0.299, t(15) = 1.118, p = .284] measures were not significant unique predictors, despite explaining 27.7% of the group variance (adjusted R^2 = 0.110).

For AwDys, the predictor variables significantly explained the dyslexic participants' performance on literacy. The regression analysis for spelling ability revealed that all three predictors together explained 51.9% of the variance (adjusted R^2 = 0.269), with just set-size [β = −.625, t(14) = −2.103, p = .008] accounting for significant unique variance unlike for crowding [β = −0.354, t(14) = −1.332, p = .206] and pre-cue use [β = 0.381, t(14) = 1.375, p = .192]. The equivalent regression analysis for reading ability revealed 47.0% of the variance (adjusted R^2 = .237) as explained by the predictors with just the pre-cue use accounting for significant unique variance [β = −0.573, t(14) = −1.931, p = .015], unlike set-size measure with marginal significance [β = −0.538, t(14) = −1.747, p = .068], in addition to crowding accounting for small and non-significant unique variance [β = −0.373, t(14) = −1.345, p = .102].

3.6 Summary Discussion

The present study compared control adults and AwDys on an orientation discrimination (search) task subjected to distractors of various spacing and quantity, whilst presented at random peripheral locations. Between AwDys and the control group, the degree of attention modulation was compared in terms of cueing, spacing, set-size (with the addition of two other set-sizes 1 and 16), in addition to their relationship with literacy measures. This was the first behavioural study to have investigated the effect of attention, and peripheral cueing on visual crowding and set-size effects, tapping directly on functions such as signal enhancement and noise exclusion using simple visual stimuli. In previous studies, the influence of each of these factors has been studied independently thus producing inconsistent results. This inconsistency could have been due to the sensitivity of the task imposed as a result of limitations within the paradigm tested or it could be the extent of severity in a given pool of AwDys. However, the present study is the very first of its kind to simultaneously investigate the effects of cueing, spacing, set-size, and task difficulty factors between a group of age and IQ matched controls and AwDys. In spite of calibrating the overall performance across conditions, and also given that the search arrays for the AwDys was presented significantly longer in duration compared to controls, a significant main effect of group on performance accuracy was evident. It was for this very reason that analyses were first split by group; so that relative (rather than absolute) performance across conditions could be compared i.e. attention modulation.

Findings from the present study showed that AwDys: (i) despite being heavily dependent on pre-cues to make accurate discrimination judgements, they used cues less successfully, i.e. they utilized pre-cues to counter effects of visual crowding, unlike the case with pre and post-cues when countering effects of set-size, (ii) were influenced by task difficulty (attentional capacity) limits only when viewing harder tilts in the presence of more distractors, and (iii) greater pre-cue dependence was associated with lower reading and spelling scores, unlike with post-cues. The key outcomes of this study are as discussed.

3.6.1 Effects of Crowding

To recap, findings from study 1 showed that compared to controls, AwDys: (i) had decreased performance when distractors were crowded, and (ii) were able to successfully utilise the pre-cues (as opposed to post and no-cues) to enhance the target signal despite the crowding. The present study backed these findings from study 1 showing a greater dependence on pre-cues when making accurate orientation discrimination judgements, especially when eliminating the effect of crowding at both levels of task difficulty. The findings on visual crowding from the present study (in addition to study 1) are consistent with those carried out previously using letter and complex letter-like stimuli (e.g. Martelli et al., 2009; Pelli et al., 2007; Spinelli et al., 2002). In particular, Spinelli and colleagues demonstrated the nature of sluggish processing speeds when CwDys were subjected to letter and symbolic stimuli under the influence of surrounding distractors. However, such slowed processing was not observed when the same procedure was carried out free of any distractors. Moreover, the authors reported of heightened reaction times concomitant with gradual increase in the inter-stimulus spacing. Similar sort of findings were also reported by Martelli et al (2009) demonstrating a significantly stronger relationship between visual crowding and reading speed in participants with dyslexia.

3.6.2 Attention Orientation

The visual search paradigm employed in the present study measured the ability to orient visual attention across various cueing (pre, post and un-cued) conditions. The findings from the present study showed a marked difference in the use of visual cues by AwDys compared to the control group. Although performance was generally on the decline for both groups, compared to the controls AwDys made fewer correct responses indicative of a problem with rapid identification of a target stimulus. In AwDys, despite being able to utilize pre-cues to produce an enhanced performance, the use of both post and un-cues yielded lower discrimination accuracies. That is, although the benefit of post-cue over un-cued conditions missed significance, the performance under the influence of post-cues slightly overhauled that of un-cued. However, in controls, the only marginal difference observed was that between pre and un-cued, whilst the rest (pre vs. post-cues and post vs. un-cues) remained not significant. These findings suggest that the pre-cues enabled the AwDys to aid enhancement of the incoming target signal during visual processing occurring either at an early and/or a much later (decisional) stage. The benefits of pre-cueing became evident even when the stimulus display contained a target stimulus on its own in the absence of distractors.

These findings based on the advantage gained from pre-cueing by AwDys are in line with an efficient signal enhancement process involved at an early visual processing stage. Just that, the importance which the post-cues play in both the early and late visual information processing is not fully elusive given the lack of cueing differences observed between pre and post-cued and/or post and un-cued conditions in controls. However, previous studies that measured the capacity to orient attention via cue validity manipulations (e.g. Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Paganoni, Turatto, et al., 2000; Buchholz & Aimola Davies, 2005, 2008) have led to conflicting results. Specifically, Buchholz & Aimola Davies (2005, 2008) did not find any significant effect of cueing attention on the capacity to orient attention in AwDys, whereas Facoetti & colleagues (e.g. Facoetti, Paganoni, & Lorusso,

2000) found a beneficial effect in AwDys in being able to utilize cues to orient their attention accordingly. Nevertheless, the finding from the current study implies that, unlike controls, AwDys happen to be highly dependent on pre-cues so as to maintain an enhanced discriminatory performance such that it is able to negate the negative impact of visual crowding.

3.6.3 Attention Focusing and Exclusion of Distractors

The present study also examined the effects of attention focusing on the ability to exclude distractors whilst the target–distractor distance remained constant. Findings showed a significant decrease in the discrimination accuracy for AwDys (unlike in controls) with subsequent increase in display set-size. This set-size effect was significantly pronounced when the discrimination was difficult despite the stimulus display being pre-cued. Conversely, for controls, this set-size effect was borderline significant across all conditions, with controls (and not AwDys) being able to fully utilise both pre and post-cues efficiently in counteracting the negative influence of set-size. The findings from the present study are consistent with just certain aspects based on the outcome of Roach & Hogben (2004, 2007). The latter previously concluded that their sample of AwDys failed to make use of the pre-cues to their advantage unlike the normal readers (Roach & Hogben, 2004), and that such cueing deficits in attentional orienting was explained by the inability to prioritise task-related sensory information during the selection process, rather than a cueing deficit *per se* (Roach & Hogben, 2007). The present study by and large conforms to both these suggestions given that AwDys were able to firstly utilise the cues to orient their attention, in addition to them having relied heavily on cues for accurate discrimination (**section 3.6.2**). Furthermore, with the effect of set-size being evident for AwDys in all three cueing conditions under harder discrimination, however it wasn’t the case under easy discriminations given the presence of a set-size effect was observed with just post-cues.

3.6.4 Relationships between Crowding, Cueing and Set-size with Literacy

An investigation was carried out to confirm whether any of the measured summary variables (cueing, spacing, and set-size) mapped onto components of literacy (spelling and reading). Findings showed a strong association between lower reading and spelling scores with that of a larger pre-cue dependence, in addition to impoverished performances in both crowding and increased set-size (even when stimulus spacing remained stable). However, there was no significant associations whatsoever between the use of post-cues and literacy measures. The extent to which reading ability correlated with the influence of both crowding was in line with that observed previously by Martelli et al (2009) within a sample of Italian CwDys. These findings go hand in hand based on the correlation observed between reading ability and the capacity to distinguish motion sensitivity against background noise (e.g. Sperling et al., 2006). Furthermore, a similar pattern of correlation was also observed between reading ability and visual attention span (e.g. Bosse et al., 2007). However, the findings from the present study demonstrating a strong correlation between literacy measures and extent of cue dependence were not something that was expected.

Based on the findings obtained from both study 1 (**Chapter 2**) and the present study, it directs us towards the realisation of a potential core difficulty in visual search in AwDys. But is this really the case?

Chapter 4: Study 3

4.1 Introduction

Differences in attention function have been well established in relation to dyslexia and based on the outcomes from many of these studies, there is evidence for noise exclusion deficits (e.g. Beattie, Lu, & Manis, 2011; Roach & Hogben, 2007; Sperling et al., 2005, 2006), difficulty in orienting attention (e.g. Valdois et al., 2004), asymmetric distribution of attention (e.g. Facoetti & Turatto, 2000; Facoetti et al., 2003c, 2008), reduced visual attention span (e.g. Bosse et al., 2007), and increased visual crowding (e.g. Martelli et al., 2009; Callens, Whitney, Tops, & Brysbaert, 2013). In fact, the magnitude of difficulties in these areas has been shown to correlate with measures of reading ability in both CwDys and AwDys. For instance, Sperling et al (2005, 2006) demonstrated that performance of motion detection in AwDys correlated with their reading ability in conditions of high noise. Bosse et al (2007) also reported of strong correlations observed between the visual attention span task performances and reading in a group of French and British CwDys. In addition, Facoetti and colleagues confirmed significant correlations linking nonword reading ability to the pace of attention shifting (Facoetti et al., 2010) and attention engagement and disengagement (Facoetti et al., 2008) in CwDys. Moreover, Martelli et al (2009) reported a strong correlation between reading rate and visual crowding.

Regardless of this, some studies have not either taken into account the confounding factors or conclusively answered how directing attention affects search performance. For instance, while certain studies have assessed perceptual functioning in both C&AwDys using either detection or identification paradigms, none have compared performance with these two paradigms targeting the same visual functions using identical stimuli (e.g. Facoetti & Turatto, 2000; Facoetti et al., 2003c; 2008). Also by utilizing stimuli such as letters to test a sample of individuals with dyslexia, some of the aforementioned studies have attributed dyslexia to poor performance in attentional functions not taking into account the demands associated in processing such stimuli especially in a dyslexic populations known to have problems with noise exclusion, attention distribution, and visual crowding. Moreover, some studies did not investigate the way the deployment of attention is related to the target eccentricity in the display. Although the stimuli were presented on an imaginary circular display controlling to some extent the eccentricity effect, this display resulted in a confounding of set-size and density, i.e. the more items, the closer they are to each other thereby equating visual crowding and not set-size effects (e.g. Roach & Hogben, 2004, 2007, 2008).

Study 2 (**chapter 3**) provided a good grounding when coming to terms with some of the deficits found common to individuals with dyslexia. Furthermore, the experimental approach offered a number of advantages over many other paradigms for investigating potential attentional impairments in dyslexia. Firstly, both the peripheral cue and the variable stimulus display were presented briefly, thereby limiting search to a single fixation precluding any scanning eye movements during stimulus presentation. Secondly, given that restricting search to a single fixation effectively equated the basic sensory representation of the stimulus display for cued (pre and post) and un-cued conditions, it was certain that this cueing benefit revealed the operation of selective visual attention. Thirdly, the stimuli used in study 2 were displayed in a circle around fixation, which allowed precise control of stimulus eccentricity and spacing effects. The study having involved an orientation discrimination task, this dimension has been well characterized both psychophysically and neurophysiologically given that a link between findings obtained with these two approaches has been established in the past (e.g. Graham, 2011).

Despite best efforts to incorporate all these methodological issues, studies 1 and 2 confirmed that AwDys were able to modulate their attention appropriately using the peripheral pre-cues but not the post-cues, the latter signifying poor noise exclusion in the late (decisional) stage. When observers acquaint themselves with the precise target location in advance, they were able to allocate all their attentional resources to that location without the need for any visual search. Thus, if the set-size effect is due to the growing number of items needed to be attentionally searched, performance for cued targets should not be affected by the number of items in the display. However, in the case of the display being un-cued, AwDys were less able to modulate their attention to the relevant target location(s) instead of all possible ones (i.e. a term generally known as spatial or location uncertainty). Studies have concluded that in the presence of spatial uncertainty, one of the primary roles of spatial attention is to exclude external noise with respect to the target region (e.g. Dosher & Lu, 2000a, 2000b). This level of spatial uncertainty about the target location produces a more noticeable degradation at low performance levels (i.e. at high noise), which is therefore thought to have been a contributing factor to the poor un-cued performance in AwDys. An obvious suggestion therefore, might be that individuals with dyslexia, when un-cued, find it difficult to search for the spatial position of the target and detect the target altogether. This goes to show that any beneficial effects of pre-cueing for AwDys (and controls) is also explained by reduced spatial uncertainty concerning the target location, as opposed to the effects of enhanced attention or distractor exclusion.

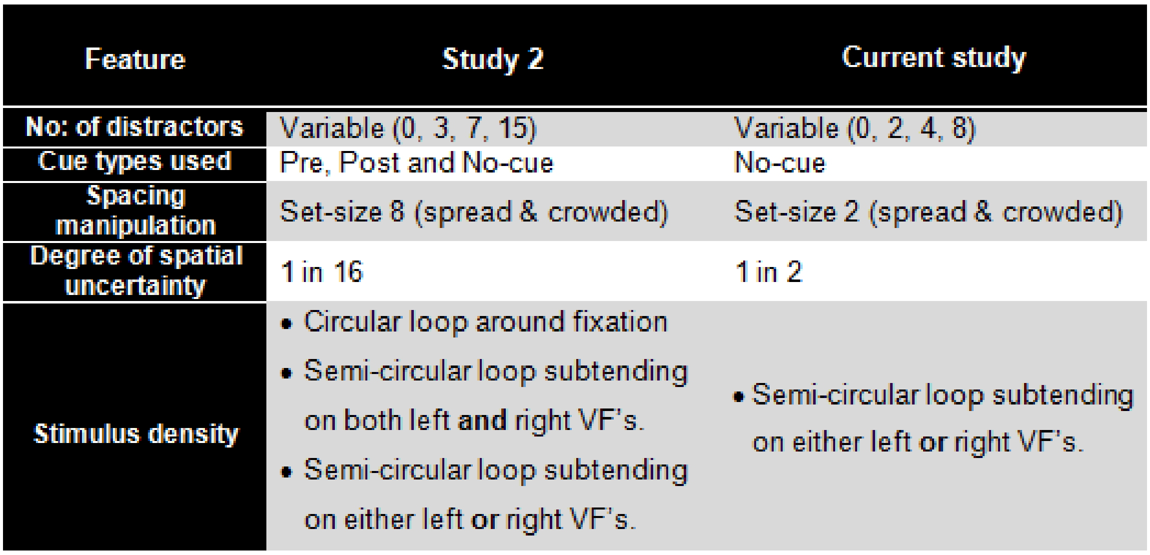
4.2 Study Objectives

In the present study, we sought to establish the replicability of the spatial un-cued performance in order to tease apart a probable functional attention based deficit in a sample of AwDys. Some aspects of study 2 (Chapter 3) were redesigned to optimise sensitivity of the search slope of participant response (in terms of orientation discrimination accuracy). **Table 4** highlights some of the crucial differences between the present study and that of study 2. In the present design there were two fixed target positions, one on the left-visual field and the other on the right-visual field. This manipulation first and foremost curtailed the potential for eye movements in the direction of a preset stimulus location. Based on one of the visual field (henceforth, referred to as VF) at which a single target was bound to appear, there were maximum of eight positions for distractors alone (four on either side of the target in a vertical meridian). This design not only eliminated both spatial uncertainty and unequal stimulus density, but also added the capability to examine both crowding as well as VF-effects.

Crowding effects – studies 1 and 2 demonstrated a severe crowding effect in AwDys with eight stimuli. It is thought that the extent of crowding induced may have been above reasonable limits (i.e. more noise present within the crowding paradigm). Therefore, the present study utilized a spacing manipulation which involved just two distractors with the same default specifications as in the study 2.

VF-effects – One key interest in the present study was to analyze the visual spatial distribution of attentional resources across both participant groups. The hypothesis tested was that of a diffused distribution of processing resources in dyslexia. Facoetti, Paganoni, & Lorusso (2000) having previously tested CwDys in a visual search task, reported findings of a more distributed (or diffused) attentional focus, given a levelled pattern of reaction times for target detection against increasing retinal eccentricity. Studies have also put forward evidence of an attention asymmetry. For instance, Facoetti and Turatto (2000)

Table 4: Variations in experimental paradigms between Study 2 and Study 3



Feature	Study 2	Current study
No: of distractors	Variable (0, 3, 7, 15)	Variable (0, 2, 4, 8)
Cue types used	Pre, Post and No-cue	No-cue
Spacing manipulation	Set-size 8 (spread & crowded)	Set-size 2 (spread & crowded)
Degree of spatial uncertainty	1 in 16	1 in 2
Stimulus density	• Circular loop around fixation • Semi-circular loop subtending on both left **and** right VF's. • Semi-circular loop subtending on either left **or** right VF's.	• Semi-circular loop subtending on either left **or** right VF's.

reported a reduced flanker effect on the left-VF, while Facoetti, Turatto, Lorusso, & Mascetti (2001) demonstrated slower reaction times to invalidly cued targets on the left-VF, a term referred to as a left-sided minineglect (Hari et al., 2001). Visual attention which is diffused (or distributed) may therefore hinder both the enhancement and retrieval of target information, in addition to poor exclusion of the distracting information during the coding stage of reading. Much of the psychophysical evidence todate points toward an asymmetric and more diffuse distribution of attention in dyslexic readers. A crucial point made by LaBerge & Brown (1989) for efficient reading was the ability to vary the size of a filter (when analysing letters in a word) in order to exclude lateral distractors. In dyslexia, any impairment in spatial attention can therefore impede information from a designated position of the VF from being processed resulting in significant interferences.

It is therefore important for studies to draw a parallel between the psychophysical and behavioural findings with literacy in order to investigate the extent to which these deficits play a part in dyslexia. For instance, Facoetti et al (2006) demonstrated a strong correlation in dyslexic readers between nonword reading accuracy and the degree of an attentional inhibition deficit of the right-VF (i.e. the finding that when cued to the left-VF, targets in the right-VF are not inhibited). Likewise, previous research has also gone on to suggest that dyslexic readers suffer more from crowding and are less effective at excluding distractors compared to controls, difficulties which had correlated with literacy abilities. However, this association between reading and the attention variable may probably be related to the overlapping dimensions which dyslexia shares with ADHD, and not directly towards literacy skills. Thus, one other limitation in studies 1 and 2 is the risk of having potentially included sub-clinical ADHD symptoms to influence overall task performance. However, the present study takes into account the potential role of sub-clinical ADHD symptomatology and its impact on task performance by controlling statistically for their presence. In the present study, we examined the relationships between four measures of literacy (word reading accuracy, word spelling accuracy, real word reading efficiency and nonword reading efficiency) and our measures of crowding, distractor exclusion and attention asymmetry.

4.3 Study Aims

Motivated by results of past research together with studies 1 and 2, the present study had three main aims explained in order of importance. With any potential effects of ADHD statistically removed, the present study therefore investigated whether:

- AwDys were able to exclude distractors efficiently in un-cued displays whilst spatial uncertainty was at its lowest. This gave us the flexibility in gaining control over visual search whilst testing for only potential detection problems in AwDys.
- There are differential VF-effects (left vs. right-VF) between groups and a possibility of it being a contributing factor towards poor distractor exclusion.
- The effects of distractor exclusion, attention distribution and crowding were strongly correlated with measures of literacy and ADHD. Using the latter measure, we evaluated if ADHD among AwDys could explain their effects rather than dyslexia.

4.4 Methodology

4.4.1 Participants

A total of 34 adult participants (16 controls and 18 AwDys) took part voluntarily in this study. Of these participants, 11 controls (7 males) and 13 AwDys (6 males) also took part previously in study two. The remainder of fresh participants were recruited from participant groups actively involved in ongoing departmental research studies, naive with respect to the purpose of this experiment. All control participants had normal or corrected-to-normal visual acuity. Apart from 3 controls and 1 dyslexic participant, the rest of the participants were right-handed. With 3 female and 2 male dyslexics having diagnosed with dyslexia in their childhood, the remaining 13 dyslexic participants received a formal diagnosis in adulthood by a qualified psychologist. With the exception of 4 controls and 2 dyslexic bilinguals, the rest of the participants were all native English speakers. All participants also had a higher educational status (on average 12.8 years of schooling, SD = 0.49) having passed the GCSE exams successfully with most of them (15 controls and 15 AwDys participants) either previously or currently enrolled in university degree programmes. This study was conducted solely on its own. The tests were conducted at two separate sessions (psychometric screening and experimentation) lasting roughly 1 – 1.5 hours for each participant. A monetary reward of £15 was offered upon completion of the study.

4.4.2 Preliminary Screening

- Ethics - The current study was approved by the Department of Psychology Ethics Committee (Aston University). All participants were subjected to a short debriefing session at the very beginning which described the main procedures so that they knew what to expect in this particular research study.
- Risk Assessment - Risk assessments were conducted similarly in the previous two studies (e.g. for Study 1 see **section 2.4.2.2**).
- Informed Consent - Processes leading up to the stage of obtaining informed consent from all participants were similar to that in the previous two studies (e.g. for Study 1 see **section 2.4.2.2**). Participants provided informed consent which conformed to the procedures approved by the Aston University's Ethics Committee on use of human participants.

4.4.3 Standardised Screening Tests

All three assessments, namely WIAT–II Spelling, WIAT–II Word Reading, and IQ (full scale) were carried out similarly to that in the previous two studies (e.g. for Study 1 see **section 2.4.3**). Among the battery of language assessments, participants from both groups were assessed on another language test, in addition to a questionnaire related to conjugating disorders (e.g. ADHD). The following tests were administered according to the specifications instructed.

4.4.3.1 Task of Word Reading Efficiency (TOWRE)

The usefulness of measuring both fluency and accuracy in word reading highlights difficulties associated with fluency independent of problems associated with accuracy. The test of word reading efficiency (TOWRE; Torgesen, 1999) is a speeded reading test (containing two subtests) designed to measure word reading accuracy and fluency. The TOWRE assessment comprised of two parts.

- Sight Word Efficiency (SWE) test provided an accuracy measure of identifying a set of 104 progressively more difficult real words (see **Appendix 4**).
- Phonetic Decoding Efficiency (PDE) test provided accuracy measure of "sounding out" or decoding a set of 63 progressively difficult pronounceable nonwords (see **Appendix 5**). Each of these subtests was administered for a period of 45 seconds.

4.4.3.2 ADHD Assessment

Given the higher comorbid nature of ADHD and reading disorders such as dyslexia (30%), this form of assessment aimed at effectively controlling for such influences. For a comprehensive evaluation of attentional functions, each participant was asked to fill in a self reporting ADHD questionnaire (see **Appendix 6**) evaluated through Diagnostic and Statistical Manual of Mental Disorders – 4th Edition (DSM-IV) criteria. The questionnaire tested for attention deficits (inattention), hyperactivity–impulsive deficits (impulsivity) and the combined type (inattention-impulsivity) described by eighteen ADHD symptoms. Their reported ADHD symptoms were tallied based on the frequency and intensity on a four-point Disruptive Behaviour Rating Scale (DBRS; Barkley & Murphy, 2006). The diagnosis of adults with symptoms of ADHD was based on the fact that they were beyond the cut-off in rating scales for ADHD disorder.

4.4.4 Selection Criteria

Based on the language assessments, the selection criteria for the AwDys group was such that each participant showed: (i) a profile of enduring reading and spelling difficulties and/or previous clinical diagnosis; (ii) no evidence of ADHD; and (iii) no evidence of other neurological and/or psychiatric problems. The control group on the other hand was required to have no previously reported problems in: (i) spelling or reading and (ii) symptoms of ADHD. In addition to those mentioned above, participants in both groups were required to have a minimum full scale IQ of 90. The psychometric measures for WIAT–II Spelling, WIAT–II Word Reading, IQ (full scale), TOWRE (SWE), TOWRE (PDE), and ADHD for both the control and dyslexic groups are summarized in **Table 5**.

4.4.5 Experimental Stimuli and Apparatus

- The stimuli (both target and distracting Gabor patches) employed were identical to study 1 in terms of its size, luminance, orientation, etc (e.g. for Study 1 see **sections 2.4.4 – 2.4.6**).
- This study utilized the exact piece of apparatus and corresponding specifications similar to that in study 1 and 2 (e.g. for Study 1 see **section 2.4.4**).

4.4.6 Set-size Configuration and Spacing

In this study, distractor set-sizes 0, 2-spread, 4 and 8 were used to exert varying task demands (**figure 31**). A single target stimulus was presented in each of these five set-size configurations which occurred 20% of the time during the entire trial sequence. The Gabor patches (target and distractors) were positioned either to the left-VF or right-VF (50% probability) of display on the circumference of an imaginary semi-circle located 5° of visual angle peripherally from the central fixation point. On either VF, the target stimulus appeared constantly at a fixed position (indicated by the arrow placeholder) whilst the distractors were assigned specific positions within the same VF as the target. In the case of display type eight stimuli, four distractors would appear adjacent to each other on both the upper and lower hemifields around the imaginary semi-circle separated by the target stimulus, all presented in a contiguous string within the same VF.

To test the effect of distractors alone, crowding effects were kept constant by separating the distractors closest to the target by an interstimulus distance of 3.5˚ visual angle from the target while the distance between distractors was constant throughout at 1.6˚ visual angle. Furthermore, the effects of crowding were manipulated while maintaining constant set-size in arrays of two stimuli under the following configurations: they were either positioned further from the target (target-distractor separation of 3.5˚ visual angle – "spread" condition) or positioned nearer the target (target-distractor separation of 1.6˚ visual angle – "crowded" condition).

4.4.7 Study Design

4.4.7.1 Variables of Interest

Participants were required to indicate the orientation of the tilted target stimuli during a two alternative forced choice task. This study consisted of one spacing and four set-size configurations with stimuli (target and accompanying distractor/s) either positioned to the left or right-VF. The probability at which the target stimuli appeared tilted either to the left or right was equally probable with each tilt associated with a given degree of difficulty. No visual cues were employed in this study. The dependent variable of interest was discrimination accuracy of the tilted target. Four independent variables gave rise to a total of 32 stimulus conditions of interest respectively, i.e.

- Set-size (0, 2 distractors-spread, 4 and 8 distractors) = 4
- Spacing (2 distractors-spread, and 2 distractors-crowded) = 2
- VF (Left, and Right) = 2
- Difficulty (Easy, i.e. -5°/+5°; and Hard, i.e. -2°/+2°) = 2

In both the practice and the main experiment, the target stimuli as well as the order of conditions varied were fully randomised between trials and for all the participants.

4.4.7.2 Calibration of Stimulus Display

Similar to study 2, the display duration (300 msec by default) was tuned to each participant's level of response accuracy during the initial practice and calibration session ahead of the main experiment. For instance, each block within the practice session consisted of two trials (one target tilting to the left and one to the right) for each of the 16 conditions, with the detection accuracy calculated for that particular block. A reduction of 10 msec occurred when the overall response accuracy surpassed 90%. The opposite was true when the overall response accuracy fell beyond 60%. This calibration of the response accuracy to the display duration therefore ensured there was no saturation in performance and therefore kept the participants overall accuracy in the range of 60% - 90%[19]. Furthermore, the short working range of the stimulus display (110 msec by default ±10 msec) prevented any scanning eye movements during the non-search attention process.

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[19] The average display durations of the AwDys and the control group differed significantly [119 msec vs. 98 msec, t(32) = 1.474, p = .018].

4.4.8 Procedure

4.4.8.1 The Experiment

Figure 31 illustrates the sequences that took place in a single trial. Each trial sequence commenced with a blank screen with a central fixation (40 msec) initiated by a key-press. The participants were instructed to fixate their eyes at this position right throughout the experiment. Shortly afterwards, a blank screen (110 msec) having an arrow on either end of the display corresponding to either one of two specific target locations was presented, followed by a stimulus display (variable duration) containing any one of the five display types (distractor set-sizes 0, 2-spread, 2-crowded, 4 or 8) along with a target stimuli. A blank fixation screen was then presented (3000 msec) enabling participant responses to be entered by indicating if the orientation of the target (compared to the perfectly vertical distractors) Gabor patch was to the left (by key-pressing "Z") or right (by key-pressing "M").

Following the presentation of each search array, the stimuli appeared unmasked. However, with the help of the practice session(s) each participant came to terms with the fact that even though there was no masking as such, during the response phase, they were required to respond within 3000 msec. Failing to do so brought up a response reminder screen requesting an input response for the target stimuli already presented. This reminder screen acted as an early pre-mask for the trial immediately after the participant response. Having this at the back of the participants mind, it ensured that they responded not just accurately but also quickly thereby enabling to minimize any response bias.

In total, fifteen blocks comprising of 40 trials each were run for the main experiment, requiring roughly 20 - 25 minutes in total for each participant.

4.4.8.2 Statistical Analysis

A one-factor ANOVA was used to quantify if both groups differed in age, IQ, and other literacy measures. Inferential statistics for comparison between groups on psychological measures was performed by a series of ANOVA’s with Bonferroni corrected post hoc comparisons whenever main analyses reached significance.

By subjecting participants to random conditions, it theoretically eliminated the possibility of

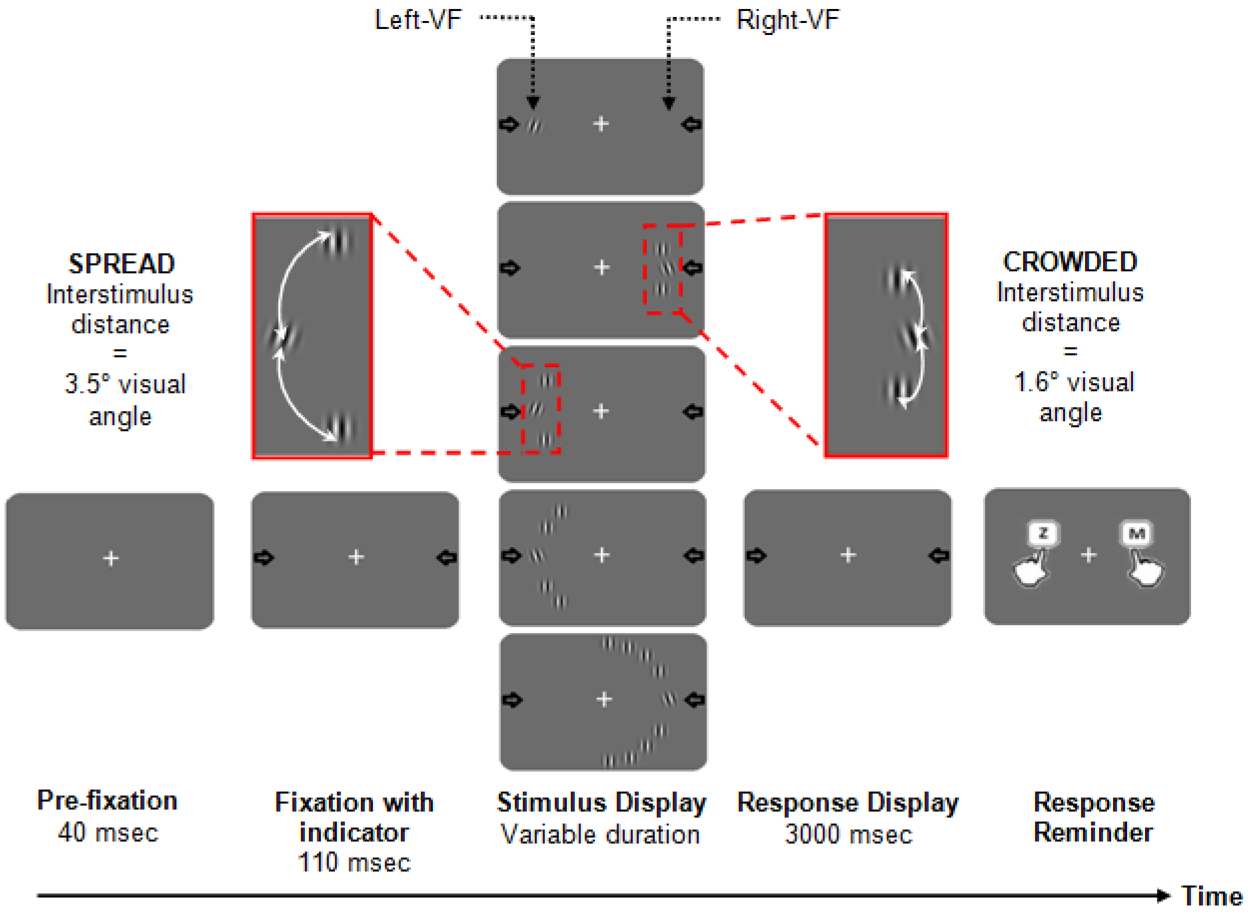

Figure 31: Schematic sequence of the visual non-search experiment in Study 3. The variable duration display with a 20% probability of any one of the five display type's occurring at a given trial. Note the level of spacing is dependent on variable interstimulus distance (1.6° or 3.5° visual angle) whilst the effect of set-size is dependent on distractor numbers alone (with a constant interstimulus distance of 3.5° visual angle).

confounding factors between experimental manipulations and participant characteristics. In a study of this kind, one might never be able to match dyslexic and control groups on an ADHD measure simply because ADHD is associated with dyslexia. In this way, participants were randomly allocated to groups either being dyslexic or control. In the case of the dyslexic group, certain participants are more likely to have stronger ADHD measures which do not always show up in the ADHD questionnaires used for screening. With regards to the present study at least (unlike studies 1 and 2), the best possible practice was to exclude AwDys (and controls) with a clinical level of ADHD as per the strict participant inclusion criteria.

However, certain individual (co-morbid) differences may go on to affect a group's overall performance while obscuring the actual effects that are present. For instance, previous estimates show that nearly as 15% of CwDys also have co-occurring ADHD, whilst around 36% of children with ADHD are estimated to have dyslexia (Shaywitz, Fletcher, & Shaywitz, 1994). With several studies going on to explain problems endured by dyslexics in terms of attention difficulties, such deficits may have actually been confounded by ADHD symptoms. In the worst case scenario, such ADHD symptoms could potentially arbitrate the effects of differences in performance variables between groups of persons with dyslexia and controls. Therefore, in the present study, it was imperative that the influence of the co-morbid ADHD factor was "minimized" or statistically "removed" altogether. The first choice of analytic tool to incorporate all these factors into one was the analysis of covariance (ANCOVA). With the co-morbid ADHD factor known to influence the dependent variables being measured, the use of ANCOVA served to "remove" the bias of this confounding variable. Thus, by the help of the latter measure, it was possible to evaluate whether ADHD among AwDys explained their effects rather than dyslexia.

However, it is important to highlight the fact that ANCOVA comes with its share of issues (e.g. Miller & Chapman, 2001). One key statistical assumption which ANCOVA firmly rests on is the issue of whether the covariate is uncorrelated with other independent variables of interest? That is, is ADHD correlated with the independent variable (i.e. groups)? Given there is a strong correlation between ADHD with that of attention measures in dyslexia (unlike in controls), by covarying ADHD (i.e. removing the variance associated with ADHD), it also serves to remove some of the variance associated with the grouping variable. In essence, this leaves less of the dependent variable's (task performance) variance to be accounted for by the independent variables (crowding, attention distribution and set-size effects). However, in the case of the present study, even after covarying for ADHD, a group effect still persisted (**section 4.5.2 onwards**). Supposing had this effect been removed after covarying for ADHD (knowing that this measure was strongly associated with the group), it then becomes uncertain as to whether this strategy also "eliminated the relevant along with the irrelevant" effects. Since it was not the case in the present analysis, it further strengthened the argument by attributing the overall outcome of the present study solely due to dyslexia, rather than ADHD, since it persisted even under conditions when ADHD was "controlled for". Nevertheless, we reanalysed psychological measures by performing a series of ANOVA measures. The results section for the current study presents statistics from ANCOVA (with the alpha-level set at $p = .05$). For the sake of avoiding repetition, the outcome of the analysis performed using ANOVA is mentioned in **Appendix 7.** A summary table at the end of each subsection compares the outcome of both the ANCOVA and ANOVA analysis. The following statistical analyses were carried out using SPSS (version 21).

4.5 Results

The results are presented in four subsections concerning: (i) psychometric assessment, (ii) visual crowding, (iii) attention distribution and noise (distractor) exclusion, and (iv) the relationship between literacy with that of crowding, set-size and attention distribution effects whilst taking into account the influence of the ADHD component.

4.5.1 Psychometric Assessment

With the exception of one male adult dyslexic[20], the study group consisted of a total of sixteen controls (7 males) and seventeen AwDys (8 males). The resultant measures when analysed across both participant groups, showed no significant differences for age (controls: M = 26.69, SD = 5.65, AwDys: M = 25.89, SD = 4.35) $F_{(1, 31)} = 0.21$, MSE = 25.04, $p = .645$, $\eta_p^2 = .00$; handedness (controls: M = 0.81, SD = 0.40, AwDys: M = 0.89, SD = 0.32) $F_{(1, 31)} = 0.37$, MSE = 0.13, $p = .544$, $\eta_p^2 = .02$; level of education (controls: M = 12.94, SD = 0.25, AwDys: M = 12.72, SD = 0.67) $F_{(1, 31)} = 1.47$, MSE = 0.26, $p = .234$, $\eta_p^2 = .04$; and IQ achievement (controls: M = 124.19, SD = 6.53, AwDys: M = 118.11, SD = 7.58) $F_{(1, 31)} = 3.18$, MSE = 28.51, $p = .088$, $\eta_p^2 = .09$. However, the groups showed a significant difference for the corresponding overall ADHD measure (controls: M = 1.44, SD

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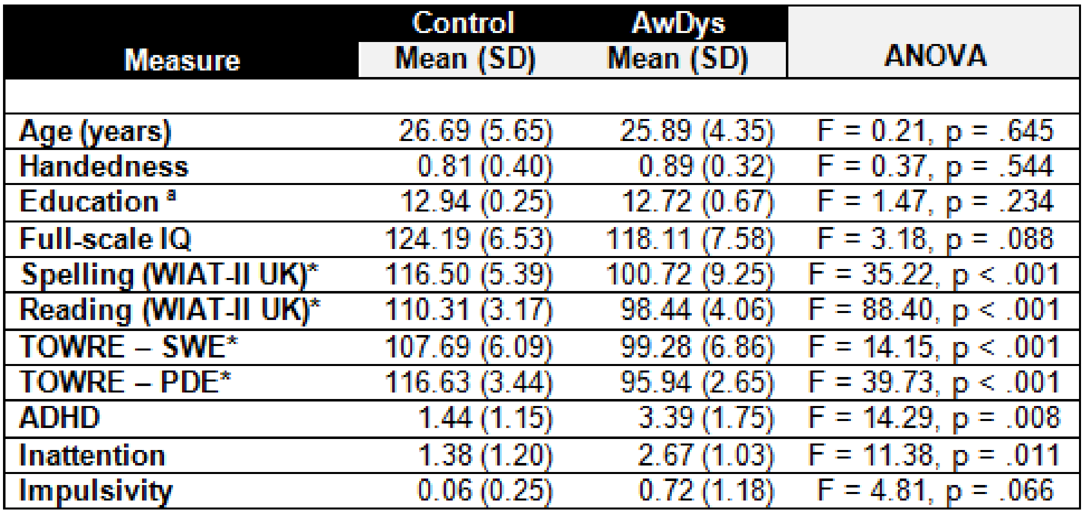
[20] The exclusion criteria from the AwDys group meant that a mean reading score of at least 2 SD below the mean age level was required. On some occasions, certain participants exhibited a significantly poor performance on either spelling or reading. This happened as WIAT-II test reached the ceiling for age. In the particular case of one AwDys, a score significantly lower than predicted on both spelling and reading was observed. Furthermore, the particular participant also showed excessive clinical thresholds for ADHD.

= 1.15, AwDys: M = 3.39, SD = 1.75) F $_{(1,\ 31)}$ = 14.29, MSE = 2.258, p = .008, η_p^2 = .31, with significant differences for inattention [(controls: M = 1.38, SD = 1.20, AwDys: M = 2.67, SD = 1.03) F $_{(1,\ 31)}$ = 11.38, MSE = 1.242, p = .011, η_p^2 = .26] but not for impulsivity [(controls: M = 0.06, SD = 0.25, AwDys: M = 0.72, SD = 1.18) F $_{(1,\ 31)}$ = 4.81, MSE = 0.767, p = .066, η_p^2 = .10]. As expected, on average the performance of the AwDys group was significantly lower for all other measures of literacy, i.e. WIAT-II word reading [(controls: M = 110.31, SD = 3.17, AwDys: M = 98.44, SD = 4.06) F $_{(1,\ 31)}$ = 88.40, MSE = 13.49, p < .001, η_p^2 = .73], WIAT-II spelling [(controls: M = 116.50, SD = 5.39, AwDys: M = 100.72, SD = 9.25) F $_{(1,\ 31)}$ = 35.22, MSE = 59.86, p < .001, η_p^2 = .52], SWE-word reading [(controls: M = 107.69, SD = 6.08, AwDys: M = 99.28, SD = 6.86) F $_{(1,\ 31)}$ = 14.15, MSE = 42.34, p < .001, η_p^2 = .31], and PDE nonword reading [(controls: M = 116.63, SD = 3.44, AwDys: M = 95.94, SD = 2.65) F $_{(1,\ 31)}$ = 39.73, MSE = 9.27, p < .001, η_p^2 = .92]. These reading and spelling measures revealed that the majority of AwDys experienced consistent problems with reading and spelling longer words, thereby reflecting poorer mean performance in the AwDys group in contrast to the control group. A comparison of demographic and psychometric data for both the controls and AwDys are summarised in **Table 5**.

Table 5: Demographic and psychometric group characteristics for Study 3. Data from a total of 16 controls and 17 AwDys data were utilized. Based on the statistics (mean scores, standard deviations and ANOVA results), findings demonstrated significantly poor literacy skills and IQ (full-scale) in AwDys compared to the control group.

The composite standard scores (SS)* predicted from IQ tests fell in range with the mean (M $_{SS}$ = 100 and SD $_{SS}$ = 14). Given the working range of TOWRE fell between 17:0 (years: months) and 24:11, the SS were calculated according to norms specified by the test manual based on the assumption that adult performance remained stable over time. [a] The level of education represents years of schooling from year 1 (infant school) to year 13 (college/sixth form).



Measure	Control Mean (SD)	AwDys Mean (SD)	ANOVA
Age (years)	26.69 (5.65)	25.89 (4.35)	F = 0.21, p = .645
Handedness	0.81 (0.40)	0.89 (0.32)	F = 0.37, p = .544
Education [a]	12.94 (0.25)	12.72 (0.67)	F = 1.47, p = .234
Full-scale IQ	124.19 (6.53)	118.11 (7.58)	F = 3.18, p = .088
Spelling (WIAT-II UK)*	116.50 (5.39)	100.72 (9.25)	F = 35.22, p < .001
Reading (WIAT-II UK)*	110.31 (3.17)	98.44 (4.06)	F = 88.40, p < .001
TOWRE – SWE*	107.69 (6.09)	99.28 (6.86)	F = 14.15, p < .001
TOWRE – PDE*	116.63 (3.44)	95.94 (2.65)	F = 39.73, p < .001
ADHD	1.44 (1.15)	3.39 (1.75)	F = 14.29, p = .008
Inattention	1.38 (1.20)	2.67 (1.03)	F = 11.38, p = .011
Impulsivity	0.06 (0.25)	0.72 (1.18)	F = 4.81, p = .066

4.5.2 Visual Crowding Effects

4.5.2.1 Main Effects

A four-factor ANCOVA between group (controls, AwDys) and set-size-eight spacing (8-spread, 8-crowded), task difficulty (easy, hard) along with display side (left-VF, right-VF) was initially assessed. Analyses indicated a significant main effect of group ($F_{(1, 31)} = 43.77$, $MSE = 0.008$, $p < .001$, $\eta_p^2 = .59$) with higher performance showed by controls and not AwDys. The influence of ADHD on the main group effect was not significant ($F_{(1, 31)} = 0.69$, $MSE = 0.006$, $p = .411$, $\eta_p^2 = .02$).

Although, significant main effects of spacing ($F_{(1, 31)} = 6.46$, $MSE = 0.009$, $p = .016$, $\eta_p^2 = 0.17$), and task difficulty ($F_{(1, 31)} = 13.02$, $MSE = 0.002$, $p < .001$, $\eta_p^2 = 0.30$) was evident, the effect of display side was not significant ($F_{(1, 31)} = 2.46$, $MSE = 0.002$, $p = .127$, $\eta_p^2 = .07$). As expected, these main effects suggested that a degraded discrimination performance was greatly influenced by the crowding of distractors and the severity imposed by the difficulty of the task irrespective of which VF the stimuli were projected on to.

Significant group interactions with spacing ($F_{(1, 31)} = 8.67$, $MSE = 0.009$, $p < .001$, $\eta_p^2 = .22$), and task difficulty ($F_{(1, 31)} = 10.66$, $MSE = 0.002$, $p < 0.001$, $\eta_p^2 = .26$) suggested a reduced performance accuracy by AwDys (more than that by controls) as the task became difficult, especially in crowded displays. However, except for the spacing, task difficulty and group interaction ($F_{(1, 31)} = 7.24$, $MSE = 0.003$, $p < .001$, $\eta_p^2 = .28$), none of the other three-way interactions reached any level of significance and nor did the four-way interaction between spacing, display side, task difficulty and group ($F_{(1, 31)} = 2.75$, $MSE = 0.002$, $p = .107$, $\eta_p^2 = .08$).

Furthermore, ADHD was not significant as a covariate for the following interactions: two way [spacing and ADHD ($F_{(1, 31)} = 0.81$, $MSE = 0.009$, $p = .376$, $\eta_p^2 = .02$); task difficulty and ADHD ($F_{(1, 31)} = 0.02$, $MSE = 0.002$, $p = .897$, $\eta_p^2 = .00$); display side and ADHD ($F_{(1, 31)} = 2.55$, $MSE = 0.002$, $p = .120$, $\eta_p^2 = .07$)], three way [spacing, task difficulty and ADHD ($F_{(1, 31)} = 0.40$, $MSE = 0.003$, $p = .531$, $\eta_p^2 = .01$); spacing, display side and ADHD ($F_{(1, 31)} = 0.04$, $MSE = 0.003$, $p = .842$, $\eta_p^2 = .00$); task difficulty, display side and ADHD ($F_{(1, 31)} = 0.47$, $MSE = 0.002$, $p = .495$, $\eta_p^2 = .02$)], and four way [spacing, task difficulty, display side and ADHD ($F_{(1, 31)} = 0.05$, $MSE = 0.002$, $p = .826$, $\eta_p^2 = .00$)]. This suggests that the influence of ADHD on these interactions were typically constant. No other main effects or interactions reached any level of significance.

4.5.2.2 Main Effects in terms of Group

In order to probe both the effects of display type and task difficulty in the main three-way interaction found in **section 4.5.2.1**, analyses were further split with respect to each group. The descriptive statistics are summarised graphically as shown in **figure 32**.

With the effects of ADHD removed, a significant effect of spacing emerged for AwDys ($F_{(1, 16)} = 14.18$, MSE = 0.007, $p < .001$, $\eta_p^2 = .47$) but not for controls ($F_{(1, 14)} = 0.108$, MSE = 0.010, $p = .747$, $\eta_p^2 = .00$). With the exception of a significant effect of task difficulty demonstrated by controls ($F_{(1, 14)} = 9.18$, MSE = 0.001, $p = .018$, $\eta_p^2 = .22$), AwDys also showed a significant effect of task difficulty ($F_{(1, 16)} = 6.97$, MSE = 0.003, $p = .009$, $\eta_p^2 = .40$) along with a spacing by task difficulty interaction ($F_{(1, 16)} = 4.97$, MSE = 0.004, $p = .006$, $\eta_p^2 = .26$). No other main effects or interactions reached any level of significance. These findings illustrate a reduced performance shown by AwDys due to the resultant crowded nature of the displays, especially when the task became harder.

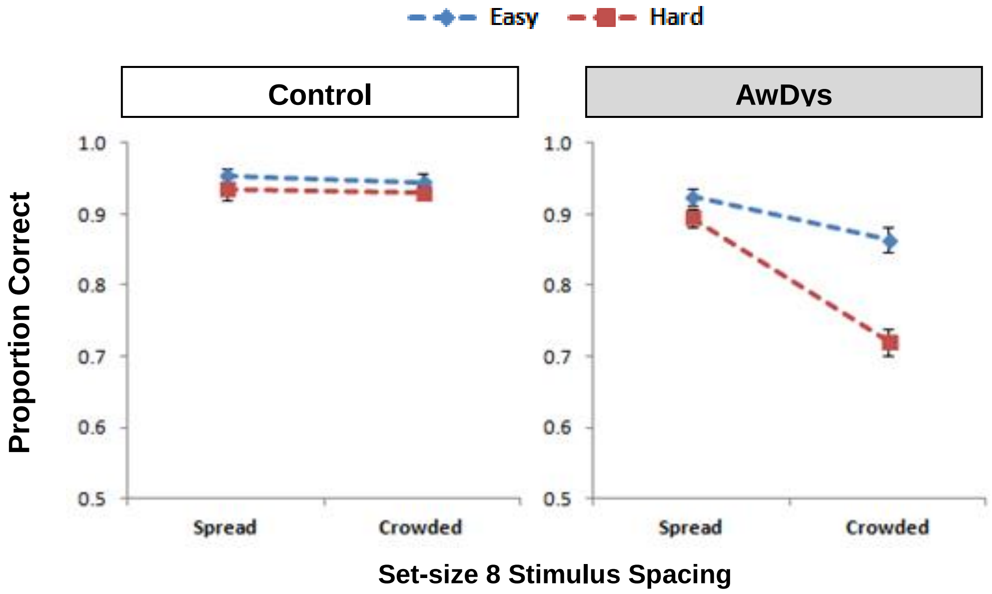


Figure 32: Interaction plots indicating performance accuracy for both controls and AwDys as a function of interstimulus spacing (crowded vs. spread) and task difficulty. The covariates appearing in the model are evaluated at the following values: ADHD = 2.47. Note that evidence for an interference based crowding effect in AwDys group as indicated by the steepness of the slope for crowded conditions. Error bars represent ±1 standard error of the mean percentage response accuracy.

With none of the interactions towards ADHD turning out to be significant, i.e. spacing and ADHD [control ($F_{(1, 14)} = 0.43$, MSE = 0.010, $p = .521$, $\eta_p^2 = .03$), AwDys ($F_{(1, 16)} = 2.693$, MSE = 0.007, $p = .120$, $\eta_p^2 = .14$)]; task difficulty and ADHD [control ($F_{(1, 14)} = 0.021$, MSE = 0.001, $p = .887$, $\eta_p^2 = .01$), AwDys ($F_{(1, 16)} = 0.022$, MSE = 0.003, $p = .885$, $\eta_p^2 = .00$)]; display side and ADHD [control ($F_{(1, 14)} = 0.034$, MSE = 0.002, $p = .857$, $\eta_p^2 = .02$), AwDys ($F_{(1, 16)} = 2.445$, MSE = 0.003, $p = .137$, $\eta_p^2 = .13$)]; spacing, task difficulty and ADHD [control ($F_{(1, 14)} = 0.831$, MSE = 0.002, $p = .377$, $\eta_p^2 = .05$), AwDys ($F_{(1, 16)} = 0.536$, MSE = 0.005, $p = .475$, $\eta_p^2 = .03$)]; spacing, display side and ADHD [control ($F_{(1, 14)} = 0.676$, MSE = 0.001, $p = .425$, $\eta_p^2 = .05$), AwDys ($F_{(1, 16)} = 0.006$, MSE = 0.004, $p = .941$, $\eta_p^2 = .00$)]; task difficulty, display side and ADHD [control ($F_{(1, 14)} = 4.517$, MSE = 0.002, $p = .082$, $\eta_p^2 = .12$), AwDys ($F_{(1, 16)} = 0.043$, MSE = 0.004, $p = .837$, $\eta_p^2 = .00$)]; and spacing, task difficulty, display side and ADHD [control ($F_{(1, 14)} = 0.079$, MSE = 0.002, $p = .782$, $\eta_p^2 = .00$), AwDys ($F_{(1, 16)} = 0.009$, MSE = 0.003, $p = .925$, $\eta_p^2 = .01$)], this was indicative of a strong evidence for an interference based crowding effect in AwDys.

4.5.3 Attention Distribution and Distractor Exclusion

4.5.3.1 Main Effects

For the sole purpose of examining the effect of set-size on orientation discriminability, a four-factor ANCOVA was carried out between group (controls, AwDys), set-size (zero, two-spread, four, eight), task difficulty (easy, hard), and display side (left-VF, right-VF). A significant main effect of group ($F_{(1, 31)} = 39.40$, MSE = 0.003, $p < .001$, $\eta_p^2 = .56$) was demonstrated despite a non-significant effect of ADHD ($F_{(1, 31)} = 0.11$, MSE = 0.005, $p < .001$, $\eta_p^2 = .56$), with higher performance showed by controls.

In addition to significant main effects of set-size ($F_{(3, 93)} = 15.557$, MSE = 0.013, $p < .001$, $\eta_p^2 = .33$), task difficulty ($F_{(1, 31)} = 11.31$, MSE = 0.004, $p < .001$, $\eta_p^2 = .27$), and display side ($F_{(1, 31)} = 10.98$, MSE = 0.002, $p < .001$, $\eta_p^2 = .26$), there were also significant two-way group interactions with set-size ($F_{(3, 93)} = 13.81$, MSE = 0.013, $p < .001$, $\eta_p^2 = .31$); task difficulty ($F_{(1, 31)} = 8.723$, MSE = 0.004, $p = .006$, $\eta_p^2 = .22$); and display side ($F_{(1, 31)} = 42.490$, MSE = 0.002, $p < .001$, $\eta_p^2 = .58$).

Furthermore, aside two-way interactions [set-size and task difficulty ($F_{(3, 93)} = 4.879$, MSE = 0.002, $p = .003$, $\eta_p^2 = .14$); and set-size and display side ($F_{(3, 93)} = 10.538$, MSE = 0.002, $p < .001$, $\eta_p^2 = .25$)], and three-way interactions [set-size, task difficulty and group ($F_{(3, 93)} = 3.849$, MSE = 0.002, $p = .012$, $\eta_p^2 = .11$); and set-size, display side and group ($F_{(1, 31)} = 30.038$, MSE = 0.002, $p < .001$, $\eta_p^2 = .49$)], a significant four-way interaction between set-size, task difficulty, display side and group ($F_{(3, 93)} = 6.714$, MSE = 0.002, $p < .001$, $\eta_p^2 = .18$) was also evident. No other main effects or interactions reached any level of significance. As expected, these main effects and interactions suggest that a degraded discrimination performance was greatly influenced by (i) the increasing numbers of distractors, (ii) the severity imposed by the difficulty of the task, and (iii) the display side (VF) on which the stimuli were projected on to.

Despite this, the effect of ADHD on the following two-way interactions [set-size and ADHD ($F_{(3, 93)} = 0.608$, MSE = 0.013, $p = .611$, $\eta_p^2 = .02$); task difficulty and ADHD ($F_{(1, 31)} = 2.490$, MSE = 0.004, $p = .125$, $\eta_p^2 = .07$); display side and ADHD ($F_{(1, 31)} = 2.602$, MSE = 0.002, $p = .117$, $\eta_p^2 = .08$)], three way interactions [set-size, task difficulty and ADHD ($F_{(3, 93)} = 1.729$, MSE = 0.002, $p = .166$, $\eta_p^2 = .05$); set-size, display side and ADHD ($F_{(3, 93)} = 0.842$, MSE = 0.002, $p = .474$, $\eta_p^2 = .03$); task difficulty, display side and ADHD ($F_{(1, 31)} = 5.167$, MSE = 0.002, $p = .080$, $\eta_p^2 = .09$)] and the four-way interaction [set-size, task difficulty, display side and ADHD ($F_{(3, 93)} = 0.972$, MSE = 0.002, $p = .410$, $\eta_p^2 = .03$)] was not significant. None of other main effects and interactions reached any level of significance. This suggests that the effect of ADHD on these interactions were typically constant.

4.5.3.2 Main Effects in terms of Group

The four-way interaction mentioned in section **4.5.3.1** (i.e. set-size, task difficulty, display side and group) was explored further using a three-factor ANCOVA [set-size (zero, two-spread, four, eight); task difficulty (easy, hard); and display side (left-VF, right-VF)] conducted for each group separately. The control group showed no main effect of set-size ($F_{(1, 14)} = 1.607$, MSE = 0.008, $p = .202$, $\eta_p^2 = .10$) although there was a significant main effect for task difficulty ($F_{(1, 14)} = 8.356$, MSE = 0.002, $p = .012$, $\eta_p^2 = .37$), and a set-size by task difficulty interaction ($F_{(3, 42)} = 3.954$, MSE = 0.001, $p = .014$, $\eta_p^2 = .22$). This suggests that a slightly reduced performance in controls was brought about as the task became harder for displays containing increasing numbers of distractors. The following main effects and interactions did not reach statistical significance: display side ($F_{(1, 14)} = 0.154$, MSE = 0.001, $p = .701$, $\eta_p^2 = .01$); set-size and display side ($F_{(3, 42)} = 0.572$, MSE = 0.001, $p = .636$, $\eta_p^2 = .04$); task difficulty and display side ($F_{(1, 14)} = 0.186$, MSE = 0.002, $p = .673$, $\eta_p^2 = .01$); and set-size, task difficulty and display side ($F_{(3, 42)} = 0.161$, MSE = 0.001, $p = .922$, $\eta_p^2 = .01$). These findings are consistent with the expectation of higher performance accuracy in displays irrespective of the number of distractors that are present on a given display side.

In contrast, the AwDys group showed significant effects of set-size ($F_{(3, 48)} = 14.466$, MSE = 0.018, $p < .001$, $\eta_p^2 = .48$); task difficulty ($F_{(1, 16)} = 5.351$, MSE = 0.006, $p = .034$, $\eta_p^2 = .25$); and display side ($F_{(1, 16)} = 11.534$, MSE = 0.003, $p = .004$, $\eta_p^2 = .42$). In addition, there were significant interactions between set-size and task difficulty ($F_{(3, 48)} = 2.257$, MSE = 0.003, $p = .029$, $\eta_p^2 = .12$); and set-size and display side ($F_{(3, 48)} = 12.291$, MSE = 0.003, $p < .001$, $\eta_p^2 = .43$). However, the interactions between task difficulty and display side ($F_{(1, 16)} = 0.765$, MSE = 0.002, $p = .395$, $\eta_p^2 = .05$), and set-size, task difficulty and display side ($F_{(3, 48)} = 1.362$, MSE = 0.003, $p = .266$, $\eta_p^2 = .08$) was not statistically significant. This poor performance by AwDys was apparent only when (i) subjected towards varying numbers of distractors, and (ii) whilst the discrimination remained difficult for a stimulus appearing on a given VF. Based on the effects observed from both groups, ADHD did not act as a significant covariate. This is indicative of a strong evidence for an interference based set-size effect especially in AwDys.

The following sub-sections investigates the resultant effect of: (i) task difficulty on efficient exclusion of noise independent on display sides (i.e. effects of set-size and display side as a function of task difficulty), and (ii) each display side on efficient exclusion of noise independent on task difficulty (i.e. visual field effects of set-size and task difficulty as a function of display side).

4.5.3.3 Influence of Task Difficulty on Distractor Exclusion

To determine whether groups differed on their ability to exclude distractors given the influence of task difficulty, the four-way interaction observed in **section 4.5.3.1** was further examined by splitting the analyses by display side and group for performance differences between task difficulties. Two separate, two-factor ANCOVAs were conducted in order to investigate whether the effects of set-size (zero, two-spread, four, eight) differed for each group (control, AwDys) as a function of task difficulty (easy, hard). The corresponding interaction plots are as shown in **figure 33**.

For controls, neither did set-size, display side, nor set-size by display side interaction reach any significance in either VF irrespective of whether the task was easy [set-size ($F_{(3, 42)} = 0.902$, MSE = 0.004, $p = .448$, $\eta_p^2 = .06$), display side ($F_{(1, 14)} = 0.044$, MSE = 0.001, $p = .836$, $\eta_p^2 = .00$), set-size and display side interaction ($F_{(3, 42)} = 0.733$, MSE = 0.001, $p = .538$, $\eta_p^2 = .05$)] or hard [set-size ($F_{(3, 42)} = 2.459$, MSE = 0.005, $p = .139$, $\eta_p^2 = .08$), display side ($F_{(1, 14)} = 0.266$, MSE = 0.001, $p = .614$, $\eta_p^2 = .02$), set-size and display side interaction ($F_{(3, 42)} = 0.042$, MSE = 0.001, $p = .989$, $\eta_p^2 = .00$)]. However, the AwDys

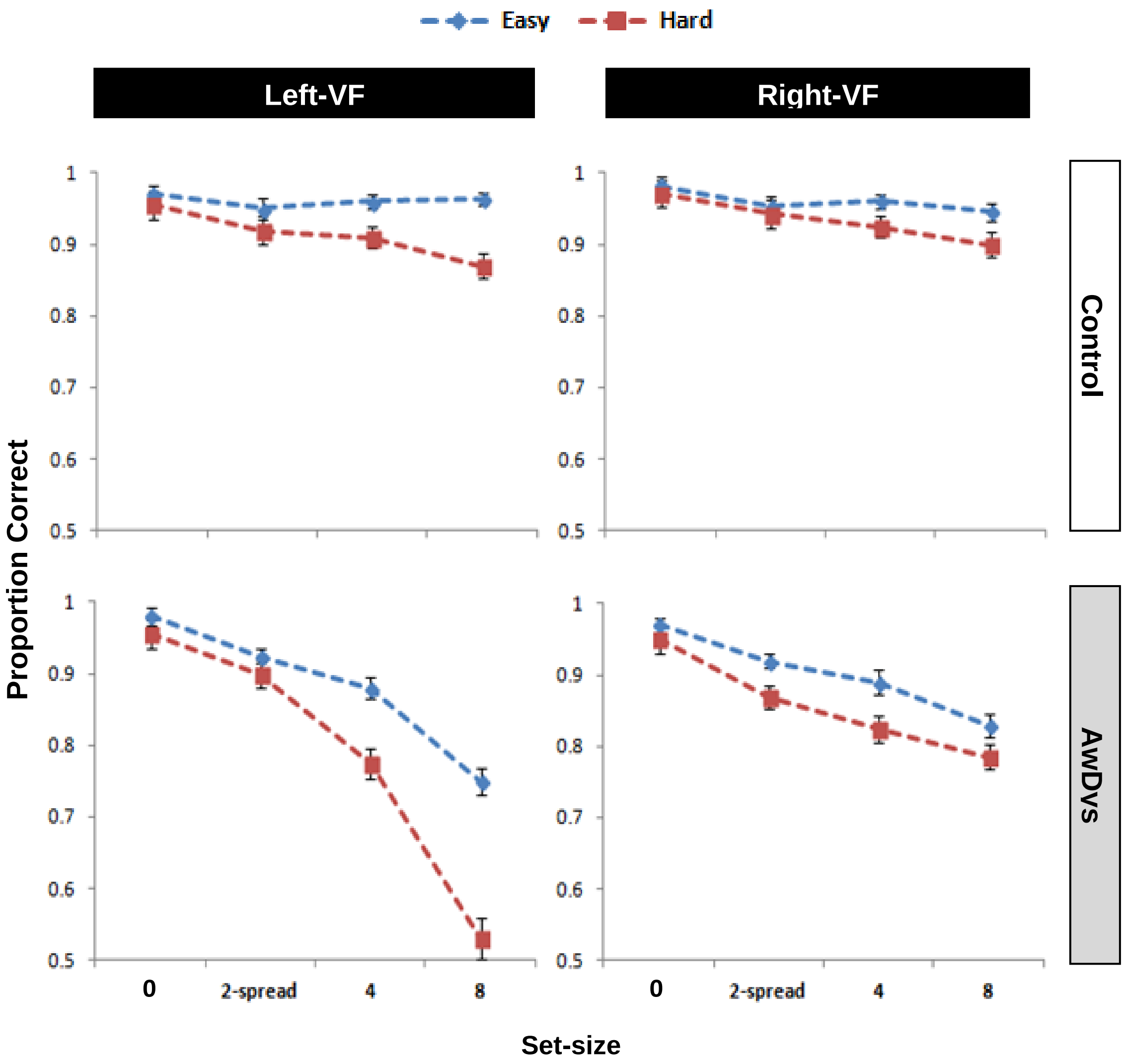


Figure 33: Descriptive statistics showing performance accuracy for both controls (top horizontal panel) and AwDys (bottom horizontal panel) for the stimulus display side conditions (left vs. right-VF) plotted as a function of set-size and task difficulty. The covariates appearing in the model are evaluated at the following values: ADHD = 2.47. Error bars represent ±1 standard error of the mean percentage response accuracy.

showed a significant main effect of set-size ($F_{(3, 48)} = 8.420$, MSE = 0.011, $p = .021$, $\eta_p^2 = .35$); display side ($F_{(1, 16)} = 6.344$, MSE = 0.002, $p = .023$, $\eta_p^2 = .28$); and set-size by display side interaction ($F_{(3, 48)} = 4.812$, MSE = 0.002, $p = .005$, $\eta_p^2 = .23$) whilst the tasks were easy. Similarly, even when the tasks were hard, AwDys demonstrated a significant main effect of set-size ($F_{(3, 48)} = 17.593$, MSE = 0.010, $p < .001$, $\eta_p^2 = .52$); display side ($F_{(1, 16)} = 6.800$, MSE = 0.004, $p = .019$, $\eta_p^2 = .30$); and set-size by display side interaction ($F_{(3, 48)} = 7.415$, MSE = 0.004, $p = .015$, $\eta_p^2 = .32$).

Moreover, with regards to these effects, ADHD was not a significant covariate in both groups. Based on the effect size/power (η_p^2) associated with each of these above measures, this pattern of results was consistent with the worse performance in AwDys being more pronounced at increasing set-sizes, irrespective of display side.

4.5.3.4 Influence of Visual Field on Distractor Exclusion

To determine whether groups differed on their ability to exclude distractors given the influence of VF effects, the four-way interaction observed previously (**section 4.5.3.1**) was further examined by splitting the analyses by task difficulty and group for performance differences between display sides. Two separate, two-factor ANCOVAs were conducted in order to investigate whether the effects of set-size (zero, two-spread, four, eight) differed for each group (control, AwDys) as a function of display side (left-VF, right-VF). The corresponding interaction plots are as shown in **figure 33**.

For stimuli displayed on the left-VF, there was no significant effect of set-size ($F_{(3, 42)} = 1.229$, MSE = 0.002, $p = .166$, $\eta_p^2 = .05$); task difficulty ($F_{(1, 14)} = 2.014$, MSE = 0.002, $p = .201$, $\eta_p^2 = .04$); and set-size by task difficulty interaction ($F_{(3, 42)} = 2.682$, MSE = 0.008, $p = .217$, $\eta_p^2 = .06$) in controls. However, with AwDys, there were significant effects of set-size ($F_{(3, 48)} = 23.047$, MSE = 0.018, $p < .001$, $\eta_p^2 = .99$); task difficulty ($F_{(1, 16)} = 4.421$, MSE = 0.016, $p = .008$, $\eta_p^2 = .64$); and set-size by task difficulty interaction ($F_{(3, 48)} = 2.672$, MSE = 0.003, $p = .008$, $\eta_p^2 = .62$).

In comparison, for stimuli displayed on the right-VF, with the exception of a significant effect of task difficulty ($F_{(1, 14)} = 20.881$, MSE = 0.012, $p < .001$, $\eta_p^2 = .98$), neither set-size ($F_{(3, 42)} = 4.463$, MSE = 0.003, $p = .139$, $\eta_p^2 = .09$) nor set-size by task difficulty interaction ($F_{(3, 42)} = 3.035$, MSE = 0.010, $p = .543$, $\eta_p^2 = .02$) was significant for controls. However, with AwDys, although there was a significant effect of set-size ($F_{(3, 48)} = 14.782$, MSE = 0.021, $p < .001$, $\eta_p^2 = .95$); and task difficulty ($F_{(1, 16)} = 23.647$, MSE = 0.013, $p < .001$, $\eta_p^2 = .51$), the interaction between set-size and task difficulty did not reach significance ($F_{(3, 48)} = 2.593$, MSE = 0.003, $p = .076$, $\eta_p^2 = .12$).

Moreover, ADHD was not a significant covariate in both groups. Based on the effect size/power (η_p^2) associated with each of these above measures, this pattern of results was consistent with the worse performance in AwDys being more pronounced at increasing set-sizes on the left compared to the right-VF, irrespective of task difficulty.

4.5.4 Set-size and Distractor Exclusion

To determine the extent to which set-sizes influenced orientation discriminability, pair-wise comparisons for set-size were carried out separately for both groups. A summary diagram highlighting the overall performance of controls and AwDys across four different set-sizes is as shown in **figure 34**. For controls, apart from the only significant difference observed between set-size zero and eight condition [t(14) = 3.592, p < .001], no other differences were significant in the remaining conditions, i.e. set-size zero and two-spread [t(14) = -1.689, p = .112]; set-size zero and four [t(14) = -1.828, p = .073]; set-size two-spread and four [t(14) = -0.555, p = .587]; set-size two-spread and eight [t(14) = -1.681, p = .114]; and set-size four and eight [t(14) = -2.606, p = .060]. These interactions reflected the fact that the performance was generally similar across all set-sizes.

On contrary, pair-wise comparisons in the AwDys group indicated significant differences between set-size zero and four [t(16) = -5.020, p < .001]; set-size zero and eight [t(16) = -10.411, p < .001]; set-size two-spread and four [t(16) = -5.767, p = .008]; set-size two-spread and eight [t(16) = -7.383, p < .001]; and set-size four and eight [t(16) = -7.018, p < .001]. The difference between set-size zero and two-spread conditions marginally missed significance [t(16) = 2.107, p = .061]. This goes to show that, in AwDys, a severe impact of the set-size effect brought about the worse performance at the largest set-size (eight), with the ability to perform better in the absence of distractors or under minimal distraction (set-size two).

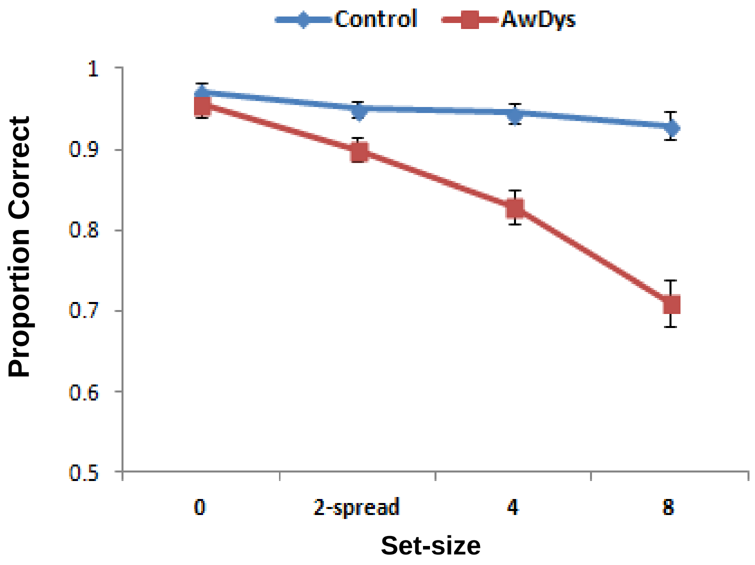


Figure 34: Line graph showing performance accuracy for both groups plotted as a function of set-size. Note the evidence for an interference based set size-effect in AwDys group as indicated by the steep drop in performance from set-size two-spread onwards. Error bars represent ±1 standard error of the mean percentage response accuracy.

4.5.5 Relationships between Crowding, Set-size and Asymmetric Attention with Literacy

In trying to evaluate whether the individual literacy measures (word reading, spelling, TOWRE-SWE and TOWRE-PDE scores) obtained for both controls and AwDys were closely influenced by crowding, display side (i.e. VF) and set-size effects, three summary variables were created based on participant performance across the task conditions. For transparency of information, easy conditions were chosen to avoid potential floor effects which were more apparent as the task became harder.

- To test the relationship between target-distractor spacing across display type-two spacing manipulation (2-spread vs. 2-crowded), the difference in search performance between spread and crowded display types acted as measure of the crowding independent of the number of distractors, i.e. crowding effect [spread – crowded displays of set-size 2].
- To test the relationship between the presence of distractors across the displays (set-size zero vs. set-size eight), the mean difference in search performance between set-size eight and set-size zero display types acted as measure of noise exclusion independent of the spacing of distractors, i.e. set-size effect [set-size 0 – set-size 8 displays].
- To test the relationship between the attention asymmetry effects across displays, the mean difference in search performance between set-size eight and zero display types in each display side acted as measure of the VF, i.e. asymmetry effect [i.e. set-size 0 (right-VF - left-VF) – set-size 8 (right-VF – left-VF)].

4.5.5.1 Partial Correlation Analyses

The three individual summary variables were estimated as predictor variables of psychometric and literacy measures, evaluated with respect to each group[21] via a series of correlation analyses (ADHD scores statistically removed) with the literacy measures (*n* = 34 in all cases, approximate critical value of *r* for a two-tailed 5% confidence level = 0.38). This set of analyses assessed the variable(s) which were most important at influencing a particular literacy measure. **Table 6** indicates the values of Pearson's *r*. **Figure 35** shows a scatter plot of the relationships for both groups.

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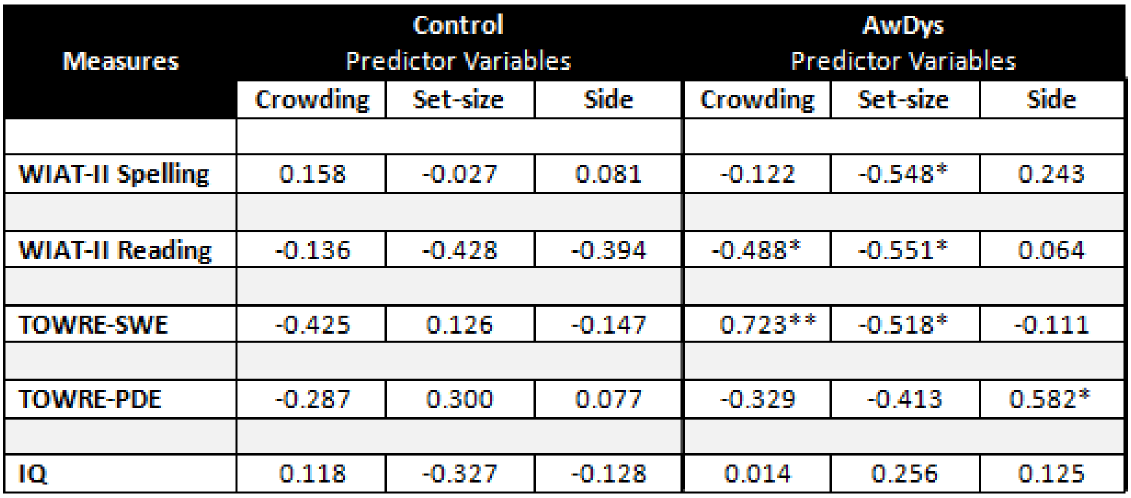
[21] One potential problem when reporting correlations for both groups is the lack of homogeneity in the data sample from which a correlation is calculated, thereby not representing the true relation between the two variables of interest (e.g. Ramus et al., 2003). For this very reason, the correlations between measures were reported for each group separately.

Table 6: Correlation matrix highlighting the relationship between the effects of crowding, set-size and display side on measures of literacy (WIAT-II spelling, reading, TOWRE-SWE and PDE), whilst controlling for effects of ADHD. Values of Pearson's r are shown with * indicating p < .05 and ** indicating p < .001.



Measures	Control Predictor Variables			AwDys Predictor Variables		
	Crowding	Set-size	Side	Crowding	Set-size	Side
WIAT-II Spelling	0.158	-0.027	0.081	-0.122	-0.548*	0.243
WIAT-II Reading	-0.136	-0.428	-0.394	-0.488*	-0.551*	0.064
TOWRE-SWE	-0.425	0.126	-0.147	0.723**	-0.518*	-0.111
TOWRE-PDE	-0.287	0.300	0.077	-0.329	-0.413	0.582*
IQ	0.118	-0.327	-0.128	0.014	0.256	0.125

As summarised in **Table 6**, controls did not show any significant correlation towards the literacy or psychometric measures, which might have been due to the smaller spread of performances, probably reflecting the achievement of a near-optimal spelling and reading strategy. The association between all three predictor variables and the IQ measure for both groups were not statistically significant, suggesting that the effect of crowding, set-size and VF impacted on spelling, reading, TOWRE-SWE and TOWRE-PDE performance directly rather than via general cognitive ability.

Nevertheless, unlike controls, AwDys showed quite a significant association when concerning effects of crowding, on reading (*r* = -0.488, p = .047) and TOWRE-SWE (*r* = 0.723, p < .001) ability; set-size, on spelling (*r* = -0.548, p = .023), reading (*r* = -0.551, p = .022) and TOWRE-SWE (*r* = 0.518, p = .033) ability; and VF on TOWRE-PDE (*r* = 0.582, p = .014) ability. **Figure 35** shows a scatter plot highlighting some of these relationships, with literacy scores increasing significantly as the influence of the predictor variables decreased. The general trend of these associations is such that, (i) the greater the impact of both crowding and set-size on performance, the lower were the scores on the literacy measures, and (ii) more the rightward asymmetry (i.e. better performance on the right vs. the left-VF), the lower the scores on the literacy measures. The pattern of correlations from these analyses is consistent with the set of analysis run without controlling for ADHD (**Appendix 7**).

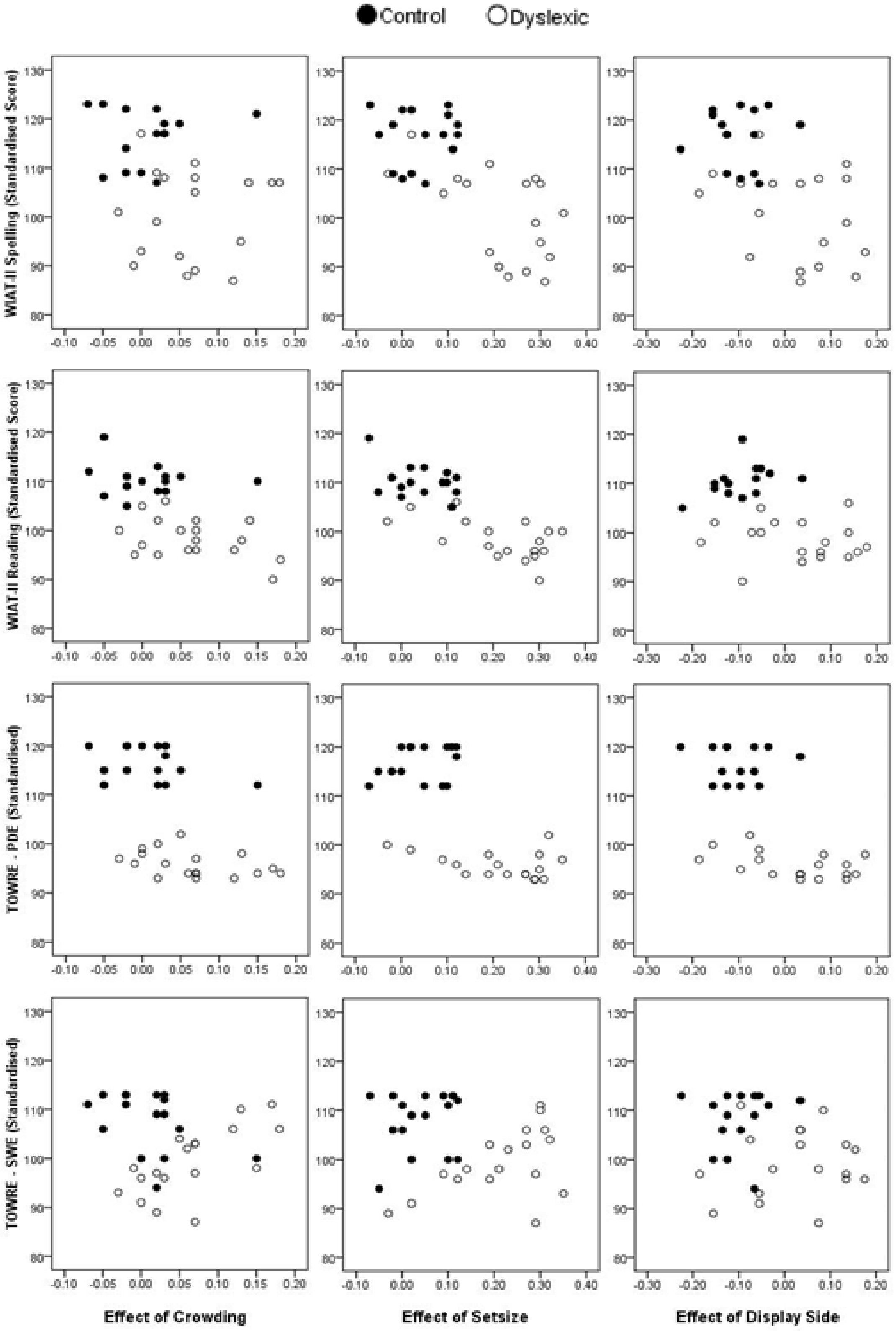


Figure 35: Scatter plots showing relationship between measures of WIAT-II Spelling, Reading, TOWRE-PDE and TOWRE-SWE achieved by controls (filled dots) and AwDys (empty dots) as a function of crowding (left panel), set-size (middle panel) and display side (right panel) effect. The effect of crowding reflects the performance difference between crowded vs. spread conditions whilst that for set-size and display side, the performance difference being set-size zero vs. set-size eight conditions.

4.5.5.2 Multiple Regression Analyses

Based on the findings from partial correlation analyses, all three variables (i.e. crowding, set-size, and asymmetry) turned out to be crucial predictors of literacy measures (spelling, reading, TOWRE-SWE and TOWRE-PDE) for AwDys, unlike for controls. These predictor variables of literacy were re-run for each group separately using multiple regression analysis (with ADHD scores statistically removed) to further assess the unique variance which each predictor adds to the regression model. When comparing these associations within different groups, the correlation confers strongly for AwDys, but not controls.

For controls, although the equivalent regression analysis for spelling revealed that the predictors explained 35.7% of the variance (adjusted $R^2 = .190$), neither did measures of crowding [$\beta = 0.149$, $t(15) = 0.497$, $p = .629$], set-size [$\beta = 0.026$, $t(15) = 0.086$, $p = .933$], nor asymmetry [$\beta = 0.056$, $t(15) = 0.187$, $p = .855$] turn out to be significant unique predictors. Same was true for reading, whereby crowding [$\beta = 0.054$, $t(15) = 0.209$, $p = .838$], set-size [$\beta = -0.405$, $t(15) = -1.575$, $p = .143$], and asymmetry [$\beta = 0.373$, $t(15) = 1.454$, $p = .174$] measures were not significant unique predictors despite explaining 35.8% of the group variance (adjusted $R^2 = 0.125$). Similarly, the equivalent regression analysis for TOWRE-SWE revealed 37.5% of the variance (adjusted $R^2 = .266$) as explained by the predictors, but neither did measures of crowding [$\beta = 0.501$, $t(15) = 1.819$, $p = .296$], set-size [$\beta = 0.293$, $t(15) = 1.066$, $p = .309$], nor asymmetry [$\beta = 0.091$, $t(15) = 0.330$, $p = .747$] turn out to be significant unique predictors. With the equivalent regression analysis for TOWRE-PDE revealing 39.7% of the variance (adjusted $R^2 = .264$) as explained by the predictors, neither did measures of crowding [$\beta = 0.440$, $t(15) = 1.595$, $p = .139$], set-size [$\beta = 0.431$, $t(15) = 1.568$, $p = .145$], nor asymmetry [$\beta = 0.120$, $t(15) = 0.438$, $p = .670$] turn out to be significant unique predictors.

For AwDys, the predictor variables significantly explained the dyslexic participants' performance on literacy. The regression analysis for spelling ability revealed that all three predictors together explained 51.2% of the variance (adjusted $R^2 = 0.362$), with just set-size [$\beta = -.460$, $t(14) = -2.108$, $p = .038$] accounting for significant unique variance unlike for crowding [$\beta = 0.048$, $t(14) = 0.220$, $p = .829$] and asymmetry [$\beta = 0.075$, $t(14) = 0.358$, $p = .726$]. The equivalent regression analysis for reading ability revealed 43.0% of the variance (adjusted $R^2 = .254$) as explained by the predictors with just set-size accounting for significant unique variance [$\beta = -0.454$, $t(14) = -1.924$, $p = .046$], unlike crowding [$\beta = 0.348$, $t(14) = 1.479$, $p = .163$] and asymmetry [$\beta = -0.059$, $t(14) = -0.275$, $p = .801$]. The equivalent regression analysis for TOWRE-SWE revealed 61.3% of the variance (adjusted $R^2 = .49.4$) as explained by the predictors with just crowding accounting for significant unique variance [β = 0.658, t(14) = 3.391, p = .005], unlike set-size [β = 0.303, t(14) = 1.556, p = .144] and asymmetry [β = −0.045, t(14) = −0.237, p = .816]. Similarly, the equivalent regression analysis for TOWRE-PDE revealed 52.9% of the variance (adjusted R^2 = .38.3) as explained by the predictors with just attention asymmetry accounting for significant unique variance [β = 0.534, t(14) = 2.577, p = .023], unlike set-size [β = -0.156, t(14) = -0.725, p = .481] and crowding [β = −0.291, t(14) = −1.358, p = .198].

4.5.5.3 Hierarchical Multiple Regression Analyses

In addition to the above, "GROUP" was included as a fourth predictor variable so as to assess whether effects of crowding, set-size, and asymmetry could explain any variance which group does not (i.e. unique variance). When considering both participant groups in tandem, these four predictor factors explained 62.5% of the variance (adjusted R^2 = 0.574). Except for crowding (β = 0.144, t(31) = 1.068, p = .294) and VF (β = 0.114, t(31) = 0.779, p = .443) factors, both set-size [β = −.404, t(31) = −2.136, p = .028], and interestingly, GROUP [β = −.435, t(31) = −2.484, p = .019] accounted for significant unique variance.

Motivated by the latter finding, the question then remains whether the predictor variables (crowding, set-size and VF asymmetry) were still able to predict a significant amount of unique variance in literacy measures, when controlled for the effect of GROUP? For this reason, a follow-up batch of sequential hierarchical regression analysis were carried out to assess how much extra variance the predictor variables (crowding, set-size and VF asymmetry) added over GROUP. In the first model of hierarchical multiple regressions GROUP was entered into the model *first* as the only predictor (i.e. variable to be controlled) with spelling measure as the dependent variable. Preliminary analyses confirmed no violation of the assumptions of normality, linearity, and homoscedasticity. This *first* model was statistically significant $F_{(1,\ 32)}$ = 35.22; p < .001 and explained 52.4% of variance in spelling. This was followed by a *second* model, where by three predictors were entered, namely crowding, set-size and VF asymmetry (i.e. variables of interest). The introduction of these three predictors in the *second* model explained 62.5%, i.e. an extra (62.5 – 52.4) 10.1% of the variance in spelling after controlling for group (R^2 change = 0.10; $F_{(4,\ 29)}$ = 12.10; p < .001). Close examination of individual predictors in these second model indicated that both GROUP [β = -0.435, t(29) = -2.484, p = .019] and set-size [β = -0.404, t(29) = -2.316, p = .028] were significantly predictive of spelling scores. The analysis was repeated individually for the remainder of dependent variables with the results summarised in **Table 7**. Overall, GROUP as a covariate, significantly accounted for variance in measures of spelling, reading, TOWRE-SWE and PDE.

Table 7: Hierarchical regression matrix relating literacy measures (WIAT-II spelling, reading, TOWRE-SWE and PDE) to effects of crowding, set-size and VF asymmetry, whilst controlling for effects of GROUP.

Dep: Variable	Pred: Variables	R	R^2	$R^2\Delta$	Sig FΔ	β	t
Spelling	**Model 1:**	.724	.524	-	-	-	-
	GROUP					-.724	-5.935***
	Model 2:	.791	.625	.102	.070	-	-
	GROUP					-.435	-2.484*
	Crowding					.144	1.068
	Set-size					-.404	-2.316*
	VF-asymmetry					.114	.779
Reading	**Model 1:**	.857	.734	-	-	-	-
	GROUP					-.857	-9.402***
	Model 2:	.903	.815	.081	.014	-	-
	GROUP					-.613	-4.984***
	Crowding					-.090	-.954
	Set-size					-.361	-2.496**
	VF-asymmetry					-.089	-.866
TOWRE-SWE	**Model 1:**	.554	.307	-	-	-	-
	GROUP					-.554	-3.761**
	Model 2:	.635	.427	.120	.132	-	-
	GROUP					-.930	-4.298***
	Crowding					.155	.933
	Set-size					.384	1.779
	VF-asymmetry					-.061	-0.337
TOWRE-PDE	**Model 1:**	.961	.924	-	-	-	-
	GROUP					-.961	-19.767***
	Model 2:	.970	.942	.017	.052	-	-
	GROUP					-.865	-12.537***
	Crowding					-.125	-2.352*
	Set-size					.044	.635
	VF-asymmetry					.123	2.127*

R – multiple correlation coefficient; R^2 - amount of variance explained by predictors variables; $R^2\Delta$ – additional variance in dependent variable; Sig FΔ – significance of the additional variance; β – standardised regression coefficient; t – obtained t-value; t-test significance (* $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$).

4.6 Summary Discussion

Study 2 (**Chapter 3**) tested the ability to which both controls and AwDys were able to modulate attention efficiently when detecting and discriminating an orientated target amidst varying distractor noise and target-distractor spacing's. As a result of the noise exclusion deficits previously demonstrated, we believe this effect could have been down to the influence of spatial uncertainty of the target given the involvement of visual search. To counteract this, the present study examined the extent to which both participant groups were able to modulate their attention (based on diverse stimulus display features) using a visual detection and discrimination task which did not involve visual search. Moreover, possible effects of ADHD have been also controlled for in the present dyslexic sample so as to avoid it from confounding the main effects of interest. In doing so, we calibrated orientation discrimination accuracy for individuals across conditions comparing each group's performance to assess the (i) impact of visual crowding, (ii) exclusion of noise/distracting stimuli (referred to as the set-size effect), and (iii) control and distribution of attention. We then assessed the relationships between crowding, set-size, the control and distribution of attention with the observed literacy variables to better understand whether the potential impact of visual attention variables impacts upon literacy skills directly.

The findings from the current study show that AwDys, when compared to controls: (i) were affected by crowding, (ii) were severely hampered by increasing noise especially on the left-VF, (iii) with the effects of crowding being significantly associated with measures of word reading. The same pattern of results was evident with the ANOVA analyses. These findings are as discussed.

4.6.1 Effects of Crowding

To recap, findings from studies 1 (**Chapter 2**) and 2 (**Chapter 3**) demonstrated that AwDys compared to controls: (i) had decreased performance when distractors were crowded, and (ii) were able to successfully utilise the pre-cues (compared to post and no-cues) to enhance the target signal despite crowding. The crowding effect demonstrated by AwDys, with performance levelling off similar to that of controls when target location was pre-cued. With these effects being evident in tasks involving visual search, it reflects that the pre-cue may possibly have facilitated participants from both groups to detect the target in addition to permit signal enhancement based on the target features. The present study backed these findings by demonstrating a detrimental effect of close spacing of distractors (i.e. crowding effect) on target discrimination in AwDys, compared to controls, even when target locations were known (given that the target stimulus was always in one of two possible locations, constantly being located on the same side as that of the distractors). Previous findings also confirm such effects occurring in crowded displays when concerning the dyslexia group, compared to the controls, that too using complex stimuli (e.g. Callens et al., 2013; Martelli et al., 2009; Pernet et al., 2006; Pilli et al., 2007; Spinelli et al., 2002). However, the finding from the present study contradicts any explanation solely concerning deficits with visual search, instead of attention enhancement or distractor (noise) exclusion.

4.6.2 Effects of Distractor (noise) Exclusion

Similar to the outcome of study 2 (**Chapter 3**), the present study also demonstrated that AwDys, compared to controls, were severely hampered by increasing distractors (noise), i.e. set-size effect. In addition to the difficulty in distractor (noise) exclusion encountered by the AwDys, the present study also demonstrated that this difficulty is asymmetric across the horizontal VFs, with lower performance observed on the left-VF as opposed to the right-VF. The finding from the present study is concordant with an asymmetric distribution of spatial attention as demonstrated previously (e.g. Hari et al., 2001). The current findings are also in line with that of Facoetti & Turatto (2000) having previously reported of a reduced flanker effect on the left-VF.

4.6.3 Relationship between Crowding, Set-size, and VF asymmetry with Literacy

The relationships between crowding, set-size and VF-asymmetry and the observed literacy variables were assessed to better understand whether the potential impact of visual attention variables impacted upon literacy skills directly. Despite having statistically removed the prospective intervening effects of ADHD symptoms, findings still for all showed a significant association between WIAT-II reading and visual crowding with just the AwDys. When considering both groups in tandem, WIAT-II reading showed a significant correlation to the set-size effect. Moreover, WIAT-II reading, WIAT-II spelling, TOWRE-SWE and TOWRE-PDE measures significantly correlated with the effect of VF asymmetry for both groups. However, upon eliminating the effect of VF asymmetry (in an independent group analyses), the resultant effects interpreted asymmetry as an effective discriminator of both groups, instead of corresponding linear relationship amid literacy measures and VF asymmetry. The same was true upon controlling for group and ADHD.

The correlations between reading and that of crowding along with set-size were in line with study 2 and those conducted in previous research (e.g. Sperling et al., 2006). Furthermore, Facoetti et al (2006) with regards to a group of dyslexics with impoverished nonword reading performance proclaimed significant correlations between nonword reading and the degree of attentional inhibition insufficiency on the right-VF. Studies which focused on neglect dyslexia (e.g. Facoetti et al., 2006) have in fact further suggested the crucial function of visuo-spatial attention focusing towards the phonological reading route, over lexical-semantic access. Despite the correlation pattern of effects demonstrated in the present study, it is of prime importance to realise that in no way does these effects denote the basis of any reading difficulties. Nonetheless, evidence from longitudinal studies has clearly associated visual attention to be a fundamental cause in dyslexia, with performances from early preschool forecasting difficulties at a later age (e.g. Franceschini et al., 2012, 2013; Plaza & Cohen, 2007).

Chapter 5:

Individual Differences

5.1 Introduction

Within the domain of developmental dyslexia, diverse set of theories explain dyslexia as a deficit in phonological, attentional, magnocellular, auditory, cerebellar and automatisation processes (Ramus, 2003). The most prominent of contending theories amongst many others is phonological deficit, a language based disorder characterised by difficulties in phonological processing which further serves to hinder the grapheme-to-phoneme correspondence (e.g. Ramus & Szenkovits, 2008). Such a deficit has previously been demonstrated by dyslexic individuals portraying poor pseudo-word reading, with irregular word reading being somewhat intact (e.g. Howard & Best, 1996; Lallier et al., 2010). Some studies have also gone on to report the exact opposite with dyslexic individuals demonstrating intact pseudo-word reading in the expense of impaired irregular word reading (e.g. Castles & Coltheart, 1996; Dubois, De Micheaux, Noel, & Valdois, 2007). It was only through such initial case studies where different reading profiles were observed, which led researchers into classifying dyslexic individuals into specific subgroups so as to reduce symptomatic diversification (e.g. Heim et al., 2008). From group analysis (e.g. Sprenger-Charolles, Siegel, Jimenez, & Ziegler, 2011) through to individual assessments (e.g. Catts, Hogan, & Fey, 2003; Zoubrinetzky, Bielle, & Valdois, 2014), findings revealed the existence of two main subtypes of phonological dyslexia, namely phonological and surface dyslexia, based on the dual-route model of reading (Perry, Ziegler, & Zorzi, 2007). Phonological dyslexia was classified as being a deficit arising from the sub-lexical route, i.e. poor grapheme-to-phoneme correspondences, whilst surface dyslexia was attributed to a deficit arising from the lexical route, i.e. poor correspondence between lexical components (Manis et al., 1996), tested using phoneme awareness tasks. However, a few studies in the recent past have argued against sub-typing with reports claiming that dyslexic individuals were impaired on both routes (i.e. double deficit), thus exhibiting mixed dyslexia (Peterson, Pennington, & Olson, 2013) thereby granting a poor description based on the entire dyslexic population (but see Manis et al., 1996).

However, recent studies propose that the reading difficulties known for dyslexic individuals to be a potential derivative from multiple sources (e.g. Ramus & Ahissar, 2012). For instance, learning to read requires the combination of a visual and a phonological language system, the former which permits visual detection of a target word among many other component letter features from surrounding letters, whilst the latter engage in identifying and constructing orally delivered words among a body of features pertaining to individual speech sounds (Schlaggar & McCandliss, 2007). Since dyslexia can arise from impairments in a number of different underlying mechanisms each sufficient to cause reading impairments, subtypes should therefore arise accordingly based on common deficits in these underlying mechanisms. A classic example of this comes from studies investigating visual attention span deficits in dyslexia, a shortcoming characterized by an inadequacy in deploying attention towards a specific spatial location. Bosse, Tainturier, & Valdois (2007) purported that a minimum of two cognitive impairments, namely phonological in combination with visual attention, could lead to dyslexia. Based on a variety of behavioural tasks, it was reported that participants (native French and English CwDys) found reading difficulties characterised by a disorder in phonology (phonological awareness, phonological short term memory, phonological fluency), visual attention span (independent of phonological difficulties), and a double deficit (both phonology and attention modalities). Moreover, many other studies have reported poor visual attention span despite intact phonological skills and vice versa in both dyslexic (e.g. Valdois et al., 2011) and typically developing (e.g. Dubois et al., 2007; Valdois et al., 2011) individuals. Group studies in CwDys have further demonstrated poor pseudo-word reading as a result of a visual span deficit in the absence of phonological problems (e.g. Dubois, Kyllingsbaek, Prado, Musca, Peiffer, et al., 2011; Peyrin, Lallier, De'monet, Baciu, Le Bas et al., 2012). In fact, efficient reading of pseudo-words entails a sufficiently large visual attention span to enable the letters (of specific sublexical components, i.e. syllabuses) in a word to be processed in parallel. Any reduction in the size of the visual attention span from its norm therefore results in poor regular word as well as pseudo-word reading, thus producing a mixed reading profile (Valdois et al., 2011).

To that end, studies have even attributed visual attention span deficits to a shortcoming in mediating perceptual attention in close alliance with phonological difficulties. For instance, Lallier et al (2010) having lent their support previously towards two key attention functions (i.e. visual attention span and shifting of visual attention), reported that AwDys having phonological deficits, with the exception of an intact attention span, was impaired on tasks which tapped on to attention sequencing, further suggesting that both phonological and visual processing difficulties coexist despite problems related to attention span.

Importantly, attentional shifting serves several other attentional functions considered to be crucial when managing episodes of target engagement (e.g. letter which requires mapping on to its correspondent speech-sound) and disengagement (e.g. detachment from the previous speech-sound to map on to a new speech-sound). Deficits in visual attentional shifting is broadly attributed to individuals with dyslexia possessing a rather weak phonological decoding ability (e.g. Breznitz et al., 2013; Buchholz & McKone, 2004; Facoetti et al., 2006, 2010; Roach & Hogben, 2007; Ruffino et al., 2010, 2014). Moreover, studies have extended findings of poor attention shifting to non-linguistic measures such as weaker noise exclusion (e.g. Facoetti et al., 2010; Ruffino et al., 2010; Sperling et al., 2005; Ziegler et al., 2009). In accordance with deficits concerning reduced attention shifts (Hari & Renvall, 2001) and weaker perceptual noise exclusion (Sperling et al., 2005), C&AwDys were reported to be particularly weak when required to swiftly engage their attention, thereby demonstrating atypical visual crowding (e.g. Geiger et al., 2008; Martelli et al., 2009; Spinelli et al., 2002). To date, attention blink (e.g. Buchholz & Aimola Davies, 2007; Facoetti et al., 2008; Lallier, Donnadieu, & Valdois, 2010) and spatial cueing (e.g. Facoetti et al., 2005, 2006, 2010; Roach & Hogben, 2007; Ruffino et al., 2014) tasks have consistently lent support towards poor visual attentional shifting in C&AwDys. Furthermore, attention studies have also gone on to relate visual crowding effects (Martelli et al., 2009), poor noise exclusion (Roach & Hogben, 2007) and attention asymmetry (Facoetti, Zorzi, Cestnick, Lorusso, Molteni et al., 2006) to be strong predictors of reading ability in dyslexia, although some studies propose in favour of a pure phonological deficit with regards to the latter (e.g. Judge et al., 2007). Since reading taps on to many different language and attentional components, it is not surprising that perceptual attentional deficits in dyslexia are open to a collection of different sources (Facoetti et al., 2003, 2005, 2010; Lallier et al., 2009, 2010; Menghini et al., 2010), whereby a single modality specific deficit (i.e. phonological, attentional or both) becomes represented by the entire dyslexic population as a whole. Taken together, this goes to show the important role played by visual attention in the acquisition of reading skills and in dyslexia.

5.2 Study Aims

The purpose of this chapter was to therefore identify potential cognitive subtypes of dyslexia. Data from the previous two behavioural studies (2 and 3) confirmed that visual attention (and not phonological) deficits influenced poor literacy (WIAT-II spelling, word reading, TOWRE-SWE and PDE) in AwDys. However, these findings cannot identify whether the weaker performance demonstrated by the AwDys, as a group, reflect a processing difficulty which is specific to the domain of visual attention. The chances are that the observed deficits in studies 2 and 3 could potentially be due to both visual and phonological difficulties being symptomatic of a domain general (rather than a specific) impairment. Importantly, the idea of a core phonological deficit on the basis of findings obtained from these studies could be confidently ruled out since the experimental paradigms employed simple orientation discrimination tasks independent of phonological and/or letter identification difficulties (known to confound the final outcome). Nevertheless, the findings from the extensive literature are to some extent inconsistent, as some of the previous research has suffered from methodological limitations such as conflating sensory (e.g. use of letter/letter like stimuli to assess phonological and/or attention deficits: Martelli et al., 2009) and attention (e.g. studies not controlling for crowding of stimuli across various stimulus set-sizes: Roach & Hogben, 2007) factors. It is beyond the scope of the current thesis to answer questions related to dyslexic sub-types and their classifications. However, a well known fact is that a complex process such as reading, promotes what is known to be a precise connection between attentional and phonological processes (e.g. Peyrin et al., 2012), and the extension of analyses reported in this chapter aims to explain the proportion of dyslexics that relate selectively to attention deficits from that of phonological deficits.

5.3 Methodology and Findings

5.3.1 Psychometric Reassessment

For the purposes of this chapter, the raw performance accuracy data were utilized from only those common participants who took part in both studies 2 and 3 respectively. Data from a total of 11 controls (7 males) and 13 AwDys (6 males) were drawn based on the effects of visual crowding (from studies 2 and 3), set-size (from studies 2 and 3), and visual field (from study 3). A one-factor ANOVA was used to quantify if both groups differed in age, education level, full-scale IQ, and other literacy measures (WIAT-II spelling, WIAT-II reading, TOWRE-SWE and PDE). Both participant groups showed no significant differences for age (studies 2 and 3), level of education (study 3), or IQ achievement (studies 2 and 3). However, the groups showed a significant difference for measures of literacy, i.e. WIAT-II spelling (studies 2 and 3), WIAT-II word reading (studies

2 and 3), SWE word reading (study 3) and PDE nonword reading (study 3). These literacy measures are indicative of reading and spelling problems, reflecting poorer mean performance in AwDys compared to the controls. A comparison of descriptive data for both groups from studies 2 and 3 is summarised in **Table 8**.

5.3.2 Individual Differences in Attention Measures

The initial analyses focused on the extent to which both control and AwDys participants demonstrated disparities in relation to measures of visual attention (crowding, set-size and visual field). Three summary variables were created based on participant performance across task conditions. For transparency of information, easy (to avoid potential floor effects which were more apparent as the task became harder) un-cued (given the fact that the search displays were left un-cued in study 3) conditions were chosen common to both.

- The difference in performance was calculated between spread and crowded display types for studies 2 (i.e. 8-spread - 8-crowded) and 3 (i.e. 2-spread - 2-crowded), generating variables "a" and "b" which acted as measures of crowding independent of the surrounding number of distractors.
- The difference in performance was calculated between relative display set-sizes for studies 2 (set-size 8-crowded - 16) and 3 (set-size 2-spread - eight), generating variables "c" and "d" which acted as measures of set-size independent of the spacing of surrounding distractors.
- The difference in performance was calculated for each visual field (i.e. left and right on either side of fixation) for study 3 (set-size 0 – 8), generating variables "x" and "y" which acted as measures of visual asymmetry.

Using these variables, individual performances based on three attention tasks was then compared between controls and AwDys, from which across group and within group (so as to spot individual differences) average *z*-scores were computed. For ease of interpretation, these computed measures were then plotted as graphically shown in **figure 36**. On visualisation of **figure 36 (panels a, b and c)**, although both groups show a pattern of results which are parallel in nature, it is clear that the AwDys in particular have a much broader distribution of z-scores on either side of the mean (zero, along the x-axis). The key however, is the number of participants showing an effect of visual crowding, set-size and/or visual asymmetry which was one standard deviation below the control group mean, thus giving an indication as to how many AwDys found it difficult to modulate their

Table 8: Demographic and psychometric group characteristics for studies 2 and 3. Data from a total of 11 controls and 13 AwDys data were utilized. Based on the statistics (mean scores, standard deviations and ANOVA results), findings demonstrated significantly poor literacy skills in AwDys compared to the control group. Groups from both studies were equally matched for age, level of education and IQ.

	STUDY 2			STUDY 3		
Measure	**Control**	**AwDys**	**ANOVA**	**Control**	**AwDys**	**ANOVA**
	Mean (SD)	**Mean (SD)**		**Mean (SD)**	**Mean (SD)**	
Age (years)	27.45 (5.83)	26.00 (5.40)	F = 0.40, p = .533	28.45 (5.83)	26.23 (4.67)	F = 1.07, p = .311
Education [a]				12.90 (0.30)	12.92 (0.27)	F = 1.47, p = .234
Full-scale IQ	125.00 (6.85)	120.07 (7.31)	F = 2.85, p = .105	125.00 (6.85)	120.07 (7.31)	F = 2.85, p = .105
Spelling (WIAT-II UK) [b]	118.54 (2.69)	*104.69 (10.64)	F = 17.57, p < .001	115.90 (6.42)	*101.53 (8.71)	F = 20.44, p < .001
Reading (WIAT-II UK) [b]	111.27 (3.15)	*100.30 (6.60)	F = 25.30, p < .001	111.09 (3.30)	*97.92 (4.31)	F = 68.49, p < .001
TOWRE – SWE[b]				107.27 (5.29)	100.07 (7.63)	F = 6.93, p = .015
TOWRE – PDE[b]				116.45 (3.58)	*101.31 (8.53)	F = 29.96, p < .001

The composite standard scores (SS)[b] predicted from IQ tests fell in range with the mean (M_{ss} = 100 and SD_{ss} = 14). Given the working range of TOWRE fell between 17:0 (years: months) and 24:11, the SS were calculated according to norms specified by the test manual based on the assumption that adult performance remained stable over time. [a] The level of education represents years of schooling from year 1 (infant school) to year 13 (college/sixth form). * T-test significance (two-tailed) p <.001.

attention accordingly. From **figure 36 (panel a)**, the percentage of AwDys demonstrating a crowding effect one standard deviation below the control group mean across both studies 2 and 3 was identical (23%), although one control (9%) was impaired based on this measure. A rather different pattern of effects was observed for the set-size measure across both studies (**figure 36 - panel b**). While 38% of AwDys demonstrated a set-size effect which was one standard deviation below the control group for study 2, this figure was much lesser in study 3 equating to 23%. Rather absurdly, 18% of control participants also showed a set-size effect which was one standard deviation below its own group mean for study 2, but not study 3. A similar pattern of results were observed for the effect of visual asymmetry (**figure 36 - panel c**), with 30% of AwDys demonstrating z-scores which was one standard deviation below the control group mean for stimuli presented on the left-visual field, compared to 15% on the right visual field. A control participant was also observed to be impaired using this criterion on the left, but not the right visual field. Taken together, apart from the measure of crowding effect, controls generally showed a commanding performance with the number of participants performing above one standard deviation of its own group mean being significantly on the higher side compared to AwDys. Interestingly, the percentage of AwDys observed with the lowest performances happen to be in study 2 (touching closer or exceeding two standard deviations below the control group mean). It is therefore logical to attribute this difficulty to the decisional uncertainty existing within the search paradigm in study 2. Moreover, the numbers of AwDys demonstrating an asymmetric effect of one standard deviation below the control group mean on the left visual field was a double of that on the right, an effect attributable to the poor ability in excluding distractors from the left compared to the right visual field.

5.3.3 Individual Differences in Phonological Measures (TOWRE)

A similar approach was then taken with the measure of nonword reading (i.e. TOWRE-PDE), an indicator of phonological performance. This gave the opportunity to work out the percentage of dyslexic readers known to have pure phonological problems. A summary variable "e" was created by converting the raw TOWRE-PDE measures into corresponding z-scores. In order to identify potential participant subgroups within the dyslexic group, a standard cut-off value of a *z*-score of less than minus one SD was imposed, consistent with the cut-off score for individual differences observed in attentional measures. **Figure 36 (panel d**) displays the pattern of effects graphically. From closer inspection, the severity of nonword performance in dyslexia is clearly evident with nearly as 38% of AwDys demonstrating poor nonword reading one standard deviation below the

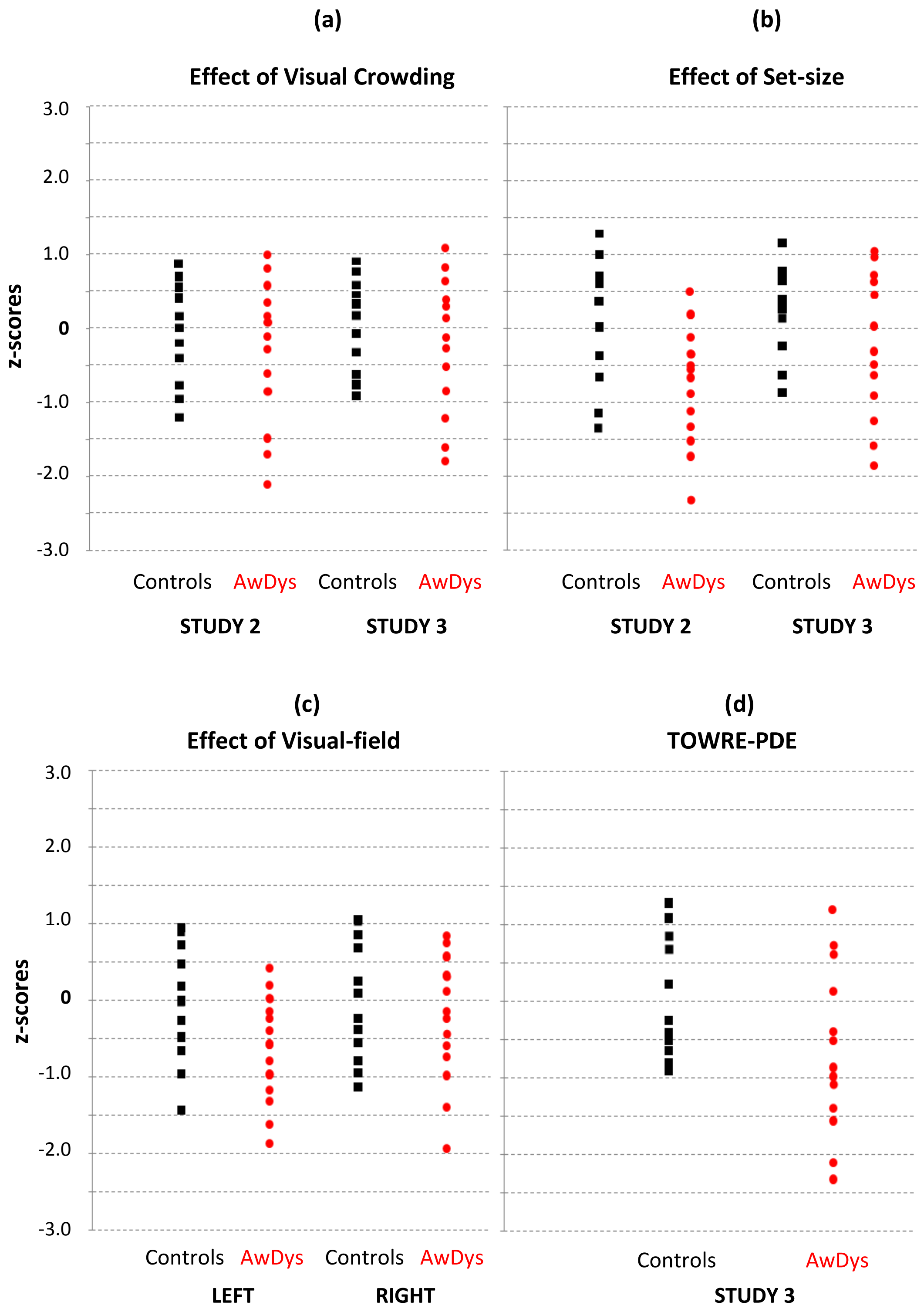


Figure 36: Vertical dot plots showing z-scores (standard deviation measure) for individual control (n = 11) and AwDys (n = 13) participants taking part common to both studies 2 and 3. Plots indicate the effect which **(a)** visual crowding, **(b)** set-size, and **(c)** visual-field, in addition to **(d)** TOWRE-PDE has on the spread of performances from the group mean. Plots for crowding, set-size and visual-field indicate attention measures whilst a pure phonological measure for TOWRE-PDE. The dotted line along 0 (x-axis) represents the group mean. Especially in the case of AwDys whose score fell below 1 SD of the control group, were therefore considered to have an impairment, either attentional or phonological.

control group mean. The severe nonword reading difficulties of 15% AwDys were also illustrated by a below average performance of two standard deviations below the control group mean. However, none of the control participants showed any impairment towards nonword reading as they performed well above the cut-off score (minus one standard deviation of its own group mean).

5.3.4 Dyslexic Sub-groups

On the whole, AwDys compared to the control group, exhibited difficulties on attention measures (crowding, set-size and visual asymmetry) as well as nonword reading (TOWRE-PDE). Given this finding, individuals with dyslexia can therefore be divided into three fractions, in that they are able to differ quantitatively based on the weaknesses in visual attention, phonology or a combination of both aspects. Therefore, the next step is to explore whether different cognitive subgroups could be recognized within the dyslexic group with regards to both the attention and phonological profiles. For this purpose, each data point (from **figure 36**) corresponding to an AwDys was closely analyzed to determine the relative distribution of each so as to classify them into the three sub-groups, i.e. poor performance due to attention deficits, phonological deficit, and/or a double deficit (attention and phonological deficit). A summary flow chart indicating the sub-group classification based on individual differences across task conditions for studies 2 and 3 is shown in **Appendix 8**. On observation of the findings in relation to each participant, the AwDys group splits into two main cognitively-distinct subgroups, with eight (62%) showing a pure attentional problem, and five (38%) demonstrating a pure phonological problem. However, there were no participants within the AwDys group demonstrating a double deficit characterized by poor attentional and phonological abilities.

5.3.5 A closer look at Dyslexic Sub-groups

The next aim was to examine the extent to which visual attention and phonological problems in the two dyslexic sub-groups were closely coupled to shortcomings in the previously observed measures of literacy (WIAT-II spelling, reading, TOWRE-SWE and PDE). Participants were divided into three groups based on individual z-scores < -1 of control group mean: (i) AwDys with an attention deficit (Dys^{Att}, $n = 8$), i.e., impaired on crowding, noise exclusion and attention asymmetry; (ii) AwDys with a phonological deficit (Dys^{Phon}, $n = 5$) i.e., impaired TOWRE-PDE reading; and (iii) control participants with none

Table 9: Correlation matrix highlighting the relationship between the effects of crowding, set-size and display side (left and right-VF) on measures of literacy (WIAT-II spelling, WIAT-II reading, TOWRE-SWE and TOWRE-PDE) and IQ, for the control and two dyslexic sub-groups (Dys^{Att} and Dys^{Phon}) whilst controlling for effects of ADHD. Values of Pearson's r are shown with * indicating $p < .05$ and ** indicating $p < .001$ (as highlighted in **bold** text).

	CONTROL				DYS^{ATT}				DYS^{PHON}			
Measures	Crowd	Set-size	Asymmetry		Crowd	Set-size	Asymmetry		Crowd	Set-size	Asymmetry	
			LVF	RVF			LVF	RVF			LVF	RVF
WIAT-II Spelling	0.555	0.653	0.166	0.415	-0.101	-0.311	0.118	0.144	-0.698	0.304	-0.356	0.382
WIAT-II Reading	0.026	-0.020	0.220	0.563	-0.538	**-0.817***	-0.655	-0.314	**-0.728***	-0.148	-0.212	0.226
TOWRE-SWE	-0.340	-0.341	0.013	0.553	**0.849***	-0.107	-0.387	-0.562	**-0.714***	0.170	0.547	0.712
TOWRE-PDE	0.154	0.318	-0.215	-0.105	0.313	**-0.964****	**-0.948****	-0.618	-0.128	**-0.836****	0.248	0.066
IQ	0.076	-0.022	0.225	0.398	0.364	0.459	0.494	0.195	0.082	0.686	0.631	-0.437

Note: Initial investigation into the use of the asymmetry variable [i.e. set-size 0 (right-VF - left-VF) – set-size 8 (right-VF – left-VF)] did not reveal any significant associations towards literacy measures for both dyslexic subgroups. However, upon considering each visual field on its own [i.e. set-size 0 (left-VF) – set-size 8 (left-VF), and set-size 0 (right-VF) – set-size 8 (right-VF)], a significant correlation was observed between a left-VF deficit and TOWRE-PDE within the Dys^{Att} attention subgroup.

impairments whatsoever on any of the two measures (*n* = 8). Note that the control adults who exhibited poor performance (i.e. individual *z*-scores < −1 of control group mean, *n* = 3) on the attention measures were excluded from the fresh control subgroup. Individual attentional (performance accuracies) and literacy (standardised scores) measures were drawn for each given participant from study 3, since this was the only study to take into consideration a variety of other literacy measures along with nonword reading ability.

5.3.5.1 Partial Correlation Analyses

The three individual summary variables for study 3 (i.e. "b", crowding measure; "d", set-size measure; and "y", measure of visual asymmetry) found previously (**section 5.3.2**), was used as predictor variables in a series of partial correlation analyses carried out separately for each sub-group (controlling for the effects of comorbid ADHD). The first batch of correlation analyses was conducted between the fresh control and Dys^{Att} sub-groups separately for each attention measure (i.e. crowding, set-size and visual asymmetry) in order to determine whether cognitive deficits within the attention modality contributed to difficulties with literacy in AwDys. The same process was repeated for a second time, but on this occasion, analyses were carried out between the fresh control and Dys^{Phon} subgroups separately for each attention measure, so as to determine whether phonological deficits contributed to difficulties with literacy in AwDys. **Table 9** indicates the values of Pearson's *r*.

For findings based on correlations between controls and the Dys^{Att} sub-group, Dys^{Att} (unlike controls) showed quite a significant association with regards to effects of crowding on TOWRE-SWE (*r* = 0.849, p = .008); set-size, on both WIAT-II reading (*r* = -0.817, p = .012) and TOWRE-PDE (*r* = -0.964, p < .001) ability; and left-VF "over-distraction" on TOWRE-PDE (*r* = -0.948, p < .001), with WIAT-II reading marginally missing significance (*r* = -0.655, p = .068). None of the other interactions for either group were significant. For findings based on correlations between controls and the Dys^{Phon} subgroup, the control group still for all did not show any significant correlations. However, the Dys^{Phon} sub-group demonstrated quite a significant association when concerning effects of set-size on TOWRE-PDE (*r* = -0.836, p < .001); and crowding on WIAT-II reading (*r* = -0.728, p = .018) and TOWRE-SWE (*r* = -0.714, p = .027), although crowding just missed significance for WIAT-II spelling ability (*r* = -0.698, p = .059).

Figure 37 shows a scatter plot of some significant relationships, with literacy scores generally increasing significantly as the influence of the predictor variables decreased. For

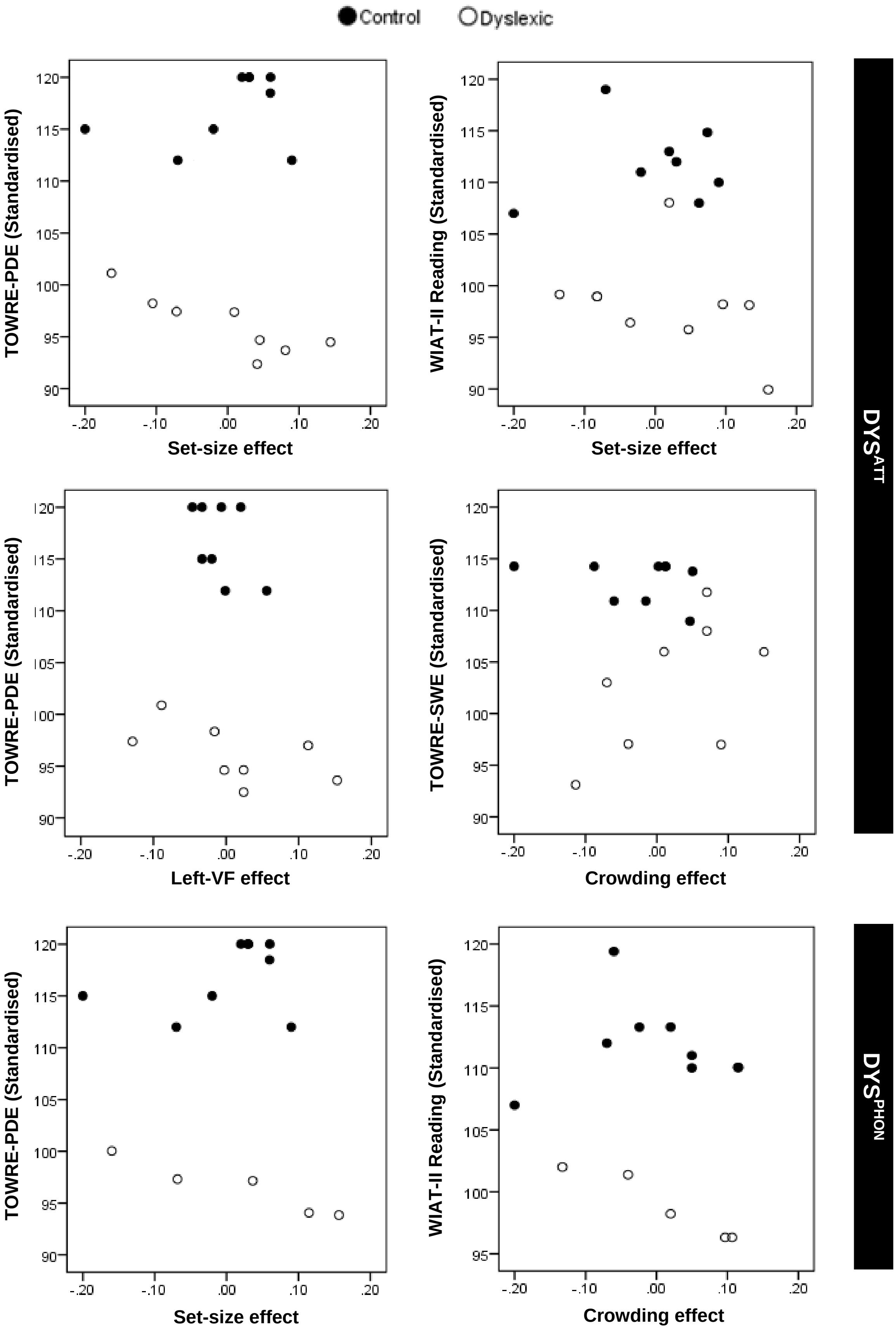


Figure 37: Scatter plots showing relationship between measures of WIAT-II Reading, TOWRE-PDE and SWE achieved by controls (filled dots) and both dyslexic sub-groups (empty dots) as a function of crowding, set-size and left-VF effect.

both groups, the association between all three predictor variables (i.e. crowding, set-size and asymmetry) and the IQ measure were not statistically significant, suggesting that the effect of crowding, set-size and visual fields impacted on WIAT-II spelling, WIAT-II reading, TOWRE-SWE and PDE performances directly, rather than by way of a general cognitive ability.

5.3.5.2 Multiple Regression Analyses (Supplementary Analyses)

Based on the findings from partial correlation analyses, crowding and set-size variables turned out to be crucial predictors of literacy measures (WIAT-II reading, TOWRE-SWE and PDE) for both the dyslexic subgroups, while a left-VF deficit was a crucial predictor of TOWRE-PDE for just the Dys^{Att} subgroup. These three predictor variables of literacy were then analysed separately using multiple regression analysis (with ADHD scores statistically removed) to further assess the unique variance which each predictor added to the regression model. However, given the unbalanced ratio of participant data between the (i) control and Dys^{Phon} (8 is to 5), and (ii) Dys^{Att} and Dys^{Phon} (8 is to 5) subgroups, the only regression analyses which became feasible to conduct was that between the control and Dys^{Att} (8 is to 8) subgroups.

For the control subgroup, although the equivalent regression analysis for WIAT-II reading revealed that the predictors explained 21.1% of the variance (adjusted $R^2 = .174$), neither did measures of crowding [$\beta = 0.233$, $t(8) = 0.218$, $p = .344$], set-size [$\beta = 0.160$, $t(8) = 0.446$, $p = .515$], nor left-VF deficit [$\beta = 0.083$, $t(8) = 0.575$, $p = .872$] turned out to be significant unique predictors. Same was true with TOWRE-SWE whereby crowding [$\beta = 0.203$, $t(8) = 0.374$, $p = .281$], set-size [$\beta = -0.119$, $t(8) = -0.425$, $p = .652$], and left-VF [$\beta = 0.073$, $t(8) = 0491$, $p = .861$] measures were not significant unique predictors, despite the explanation of 30.0% in subgroup variance (adjusted $R^2 = 0.243$). Similarly, in spite of an equivalent regression analysis for TOWRE-PDE revealing 20.4% of the variance as explained by the predictors (adjusted $R^2 = .152$), neither did measures of crowding [$\beta = 0.217$, $t(8) = 0.184$, $p = .427$], set-size [$\beta = 0.158$, $t(8) = 0.437$, $p = .569$], nor a left-VF deficit [$\beta = 0.098$, $t(8) = 0.512$, $p = .791$] turned out to be significant unique predictors.

On comparison with the Dys^{Att} subgroup, the predictor variables significantly explained participants' performance on literacy. The regression analysis for WIAT-II reading ability revealed that all three predictors together explained 50.5% of the variance (adjusted $R^2 = .474$), with just set-size [$\beta = -.589$, $t(8) = -1.983$, $p = .018$] accounting for significant unique variance unlike for crowding [$\beta = -0.480$, $t(8) = -1.081$, $p = .290$] and left-VF deficit [β = 0.497, t(8) = 1.383, p = .261]. The equivalent regression analysis for TOWRE-SWE ability revealed 67.0% of the variance (adjusted $R^2 = .593$) as explained by the predictors with just crowding accounting for significant unique variance [β = −0.793, t(8) = −2.400, p = .006], unlike set-size [β = −0.338, t(8) = −0.646, p = .364], and left-VF deficit [β = 0.276, t(8) = 0.303, p = .482]. Interestingly, the equivalent regression analysis for TOWRE-PDE ability revealed 83.5% of the variance (adjusted $R^2 = .749$) as explained by the predictors with both set-size [β = -2.179, t(8) = -5.422, p < .001] and left-VF deficit [β = −1.925, t(8) = −3.314, p < .001] accounting for significant unique variance, but not crowding [β = −0.178, t(8) = −1.012, p = .386].

5.4 Summary Discussion

Studies 2 (**Chapter 3**) and 3 (**Chapter 4**) tested the ability to which both controls and AwDys were able to modulate attention efficiently when detecting and discriminating an orientated target amid varying distractor noise and target-distractor spacing’s, aided either by visual search (study 2) or without (study 3). Findings from both studies demonstrated deficits pertaining to visual attention where AwDys was found to struggle in symmetrically distributing their attention, with more persistent deficits observed when required to exclude external noise and overcome the crowding of distractors. The present chapter aimed to take the analysis one step further by analysing the overall performance of the two groups of participants (controls and AwDys common for both studies 2 and 3). This was achieved by focusing on individual differences among AwDys so as to investigate the relative contributions played by both visual attention and phonological deficits, either in isolation or as a combination, towards dyslexia. Whilst the averaged data could imply an underlying solitary deficit in dyslexia, it is possible that each dyslexic individual had multiple deficits. For this very reason, individual data were considered with deficits expressed for individual dyslexic participants in terms of z-scores assessing the distinction between controls and subgroups of dyslexia.

The current chapter questioned the bearing of both attentional and phonological reading profiles to identify homogeneous subgroups of dyslexic adults. It was observed that adults within the dyslexic group split into two distinct cognitive subgroups, attentional and phonological, but not the double deficit type. Although both the dyslexic subgroups were characterised by similar cognitive problems, yet they exhibited very distinct reading (word and nonword) performances, with significant correlations observed within the attentional compared to the phonological subgroup. Furthermore, the two contrasted dyslexic subgroups were in line with recent brain function studies where similar dyslexic subgroup dissociations were reported at the neural level (e.g. Peyrin et al., 2011, 2012). On the whole, the data taken from individuals common to both studies 2 and 3 clearly defines both subgroups and their relations with normal word reading, with the exception of a rather unclear relationship between left visual field asymmetry and nonword reading within the phonological subgroup. Nevertheless, this left visual field asymmetry together with both visual crowding and set-size deficits, just goes to indicate how poorly visual attention is distributed in dyslexic individuals especially when reading nonwords, a finding which is extremely common within the cohort of attention deficits in dyslexia.

Chapter 6:

Study 4 Proposal

6.1 Introduction

Several studies within dyslexia literature have focused on deficits with regards to aspects of the spotlight mode of visual attention. The spotlight of attention, or otherwise known as the attentional focus, is highly flexible, in that it is able to change its size so as to include stimuli at various spatial extents (e.g. Ronconi, Basso, Gori, & Facoetti, 2014). Attention happens to be either potent within a specific section of the visual field (focused attention), or spread across a large part of the visual field (diffused attention). For instance, when learning to read, the correct detection of a letter within a word (or a word within a passage of text for that matter) requires accurate control of the size of the attention focus in order to exclude the distractor information effectively (e.g. LaBerge & Brown, 1989). Any excess stimulus inhibition in the left-VF (i.e. left inattention) in parallel to a deficient right-VF stimulus inhibition (right over-distractibility) serves to manipulate the process concerned with word decoding either by masking the letter stimuli present on the left, or by an inability to inhibit peripheral distracting stimuli from the right analogous to the normal route of reading (e.g. Facoetti et al., 2001). Studies which employed linguistic (among various other) stimuli, have demonstrated asymmetric orientation of attention both in children and AwDys (e.g. Facoetti et al., 2000). Further to this, a group of children with impaired nonword reading was reported to have an asymmetrical attentional spotlight, with attention being more focused on the right, compared to the left-VF (e.g. Facoetti & Turatto, 2000; Facoetti et al., 2006). Moreover, spatial attention deficits in dyslexia have also been repeatedly demonstrated in the poor shifting of visual attention, resulting in pseudo-word reading difficulties in dyslexia (e.g. Bosse et al., 2007; Cestnick & Coltheart, 1999; Facoetti et al., 2006, 2008; Vidyasagar & Pammer, 2010). Therefore, any modulatory deficits of this nature could potentially result in perceptual difficulties especially in tasks requiring a proficient noise filtration/exclusion mechanism.

In order to better quantify the extent of attention filtering within the fold of cognitive neuroscience, many research studies in the past have recruited neuroimaging techniques (i.e. fMRI) to assess the neural correlates of cognitive function (attention) with high spatial precision. Much of the neuroimaging work carried out looked at enhanced processing of visual stimuli following the deployment of attention (thereby facilitating both detection and identification of the attended stimuli), compared to that when withdrawing attention from the target stimulus (e.g. Downing, Liu, & Kanwisher, 2001; Bledowski, Prvulovic, Goebel, Zanella, & Lindena, 2004; Bles & Jansma, 2008). The link between neuronal activity and selective visual attention was initially reported in areas such as the parietal, temporal, and prefrontal cortical regions of the human brain (e.g. Nobre, Coull, Walsh, & Frith, 2003), with prefrontal areas reported to be involved in attention allocation (e.g. Indovina & Macaluso, 2007) whilst the posterior parietal cortex was associated with shifts of visual attention (e.g. Greenberg, Esterman, Wilson, Serences, & Yantis, 2010). Importantly, studies of recent times have also investigated the outcome of the attentionally excluded stimuli (e.g. Lu, Li, Tjan, Dosher, & Chu, 2011) with the filtering of spatially distracting stimuli reported to be under the control of the parietal region (e.g. Akyüreka, Vallinesa, Lina, & Schubö, 2010; Friedman-Hill, Robertson, Desimone, & Ungerleider, 2003; Wojciulik & Kanwisher, 1999). Findings generated from studies of this kind conducted within the dyslexic population have reported potential deficits concerning the magnocellular system (e.g. Yamamoto et al., 2013), in addition to reduced visual attention span which strongly correlates towards a (left) superior parietal disorder (e.g. Lobier, Peyrin, Pichat, Bas, & Valdois, 2014; Peyrin, Demonet, N'Guyen-Morel, Bas, & Valdois, 2011; Peyrin, Lallier, & Valdois, 2008), but rarely have neuroimaging studies investigated the neurobiological correlates of the attention focusing deficits in dyslexia.

For the most part of the fMRI studies conducted to-date have targeted two corticoparietal regions of interest (ROIs) namely, fusiform face area (FFA – selective response towards facial identification, Kanwisher et al., 1997), and the parahippocampal place area (PPA – selective response towards objects and houses, Epstein & Kanwisher, 1998). With the activity from these regions being stimulus dependent, many researchers have made use of this as a neural indicator for assessing attention modulation mainly in control participants (e.g. Kanwisher et al., 1997; O'Craven & Kanwisher, 2000; Wojciulik et al., 1998; Zhang, Liu, Huber, Rieth, Tian, & Lee, 2007). Such paradigms have offered an added flexibility to measure the cortical response towards the exclusion of (irrelevant) distractors during object-based (O'Craven, Downing, & Kanwisher, 1999) and feature-based (O'Craven et al., 1997) attention. In most cases, faces were observed to capture visual attention when in competition with other surrounding non-face stimuli (e.g. Langton, Law, Burton, & Schweinberger, 2008). Studies have also reported of controls finding it relatively easy when detecting face targets, but not other objects, within a crowded display of diverse distractors (e.g. Hershler & Hochstein, 2009; Hershler, Golan, Bentin, & Hochstein, 2010, but see Maurer, O'Craven, Le-Grand, Mondloch, Springer, Lewis, & Grady, 2007).

More specifically, a topic of interest for the present study was an earlier work carried out by Wojciulik et al (1998) questioning the extent to which control participants were able to modulate covert (selective) attention towards faces, under conditions where the face stimuli turned out to be task relevant versus that when being irrelevant. The participants were subjected to a series of stimulus displays, with each display consisting two faces (of ordinary people) and houses conforming to both horizontal (houses) and vertical (faces) configurations on either side of fixation, with each pair being identical (50% of the time) independent of the other stimulus pair. The participants were then required to discriminate between faces and houses (in separate experimental blocks) indicating if the pair of targets (e.g. faces) was similar while ignoring the distractors (e.g. houses) by maintaining foveal fixation. Based on this finding, the researchers reported a significant face fusiform area activity when participants attended to faces compared to houses. That is, in conditions where faces happened to be irrelevant, a reduced face processing was evident unlike when having fully attended (in conditions were houses were task irrelevant). Furthermore, with the face fusiform activation being not consistently elevated despite the presence of face stimuli in both matching tasks, this response was indicative of covert attention allocation when the perceptually relevant (face) stimuli were present outside the focus of visual attention.

6.2 Study Objectives

Based on the findings from the behavioural studies conducted, the performance of AwDys on visual search (i.e. study 2) and non-search discrimination (i.e. study 3) tasks using simple visual stimuli was significantly affected by increased visual crowding and set-size. In study 2, the lower performance by AwDys in conditions of greater task difficulty and higher set-size, in addition to the higher performance with pre-cue use, was consistent with the idea of reduced visual attentional resources (Bosse et al., 2007). However, the exact reason as to how such diminished attention resources could bring about a poor riddance of the set-size effect despite pre-cueing was somewhat unclear. Should such effects be a result of a reduced attentional span (i.e. the number of individual visual elements that can be processed simultaneously) despite intact orienting capability, even then the inability to overcome the set-size effect cannot be explained by reduced attention span in un-cued conditions. Moreover, the larger set-size effect in un-cued conditions cannot be fully interpreted in terms of a significantly diffused distribution of attention in dyslexia (Facoetti et al., 2001). Taking both factors (i.e. reduced attentional resources and attention diffusivity) into consideration, the performance of un-crowded displays was expected to be similar across both groups should the overall attentional resources remain equal, with the exception of it being distributed differently. Nevertheless, crowding effects across both participant groups remained stable, perhaps due to the spread displays being not entirely un-crowded for AwDys. However, none of the three studies measured the critical distance of crowding. Given that AwDys were able to orient their attention using the pre-cues (study 1), it could probably come down to the fact that they were unable to narrow down their attention efficiently as the controls. This probably implies why AwDys were less able to exclude/filter distractors which they were not expected to focus at (study 2). Therefore, the question remains as to whether AwDys have a difficulty in narrowing down their visual attention focus (as discussed based on findings from study 3)?

With the help of functional neuroimaging, the present study investigated the extent to which neural activity, within the fusiform face area, was reduced (between a group of AwDys and controls) when subjected to task specific (face) stimuli outside the focus of visual attention. The present study replicated the work carried out previously by Wojciulik et al (1998) given the relative strengths of both the methodology and technique involved.

- Using a variant of set-size: A typical visual search task requires participants to detect a target surrounded by an array of distractors, with the set-size effect equating elevated response times and lower detection and/or discrimination accuracies, both which occur with increasing distractor numbers (e.g. Carrasco & Yeshurun, 1998). The nature of involuntary preattentive processing, visual target search, coupled with signal enhancement and noise exclusion mechanisms is what gives rise to this set-size effect (e.g. Wolfe & Horowitz, 2004). As easy as this may seem from a behavioural standpoint, however in actual fact, studies in the past have found it rather difficult when depicting the neural basis of the set-size effect for the very reason that changes in set-size is predominantly accompanied by alterations in perceptual and cognitive task demands. For instance, any variation in the set-size invariably alters the quantity of visual information present within the stimulus display. This can potentially (i) transform the neural activity present within underlying lower-level visual regions and/or separately employ other non-selective attentional localities like the posterior parietal cortex (e.g. Jerde et al., 2008), and (ii) alter target selection demands thereby regulating the quantity of attentional targets, both attributes which could potentially give rise to a set-size effect in various brain regions (e.g. Jerde, Ikkai, & Curtis, 2011).

However, based on the study by Wojciulik et al (1998), the noise present within their paradigm was not precisely equivalent to the distraction exerted in terms of varying set-size, rather it was attributed to the different pairs of non-face (houses) stimuli being presented alongside the face stimuli. With their task requiring participants, in separate groups, to exclude faces (while focusing attention on the houses) and houses (while focusing attention on the face stimuli), the finding that the main locus of face perception to be the face fusiform area undergoing modulation by covert attention, further offers an advantage when utilizing face stimuli as the prime target of interest vs. house pairs (as the distractor) in the present study.

- <u>Use of task specific stimuli</u>: Many studies in the past have opted to use faces as a more preferred form of stimuli, especially in tasks where participants were required to focus their attention appropriately when discriminating between two or more target stimulus types presented simultaneously. The responsive and discriminatory measures of face processing in humans make them ideal from a practical perspective. That is, given the nature of such processes being carried out for the purposes of social cognition and interaction, in addition to the ease with which such stimuli are perceived (over more complex stimuli such as Gabor patches), the faces therefore symbolise a unique stimulus category for human perception, possibly more so than the process of directing visual attention itself (e.g. Vuilleumier & Schwartz, 2001). Furthermore, faces makes it a suitable candidate especially in tasks which calls for stimulus processing in conditions where alternative forms of distractors are expected to be ignored with relative ease (e.g. Devue, Laloyaux, Feyers, Theeuwes, & Bredart, 2009). With faces demanding the need for attention more than non-face stimuli, studies have demonstrated this to be the case even in conditions when faces did not crop up at potential target relevant locations (e.g. Palermo & Rhodes, 2007), in addition to the presence of varying perceptual load (e.g. Lavie, Ro, & Russel, 2003). The enhanced excitatory processing of focused attention explicit to face stimuli (e.g. Palermo & Rhodes, 2007) coupled with the selective inhibitory processing of attention towards distractors (e.g. Machado, Guiney, & Mitchell, 2011) has accounted for the difficulty when ignoring faces.

- Combinatorial analysis: With the exception of a few studies (e.g. Wojciulik et al., 1998), many have employed the simultaneous use of both neuroimaging and behavioral experiments to closely inspect attention-mediated vs. perceptual awareness, by reporting brain activity measures which integrates with the (biased) participant responses (e.g. Jerde et al., 2011). Using an extended version of the fMRI paradigm, the behavioural paradigm in the present study examined the extent of attention focusing under conditions of varying "noise" (by varying the degree of face familiarity via face plane rotations). Crucially though, face processing in peripheral regions was known to be limited, as opposed to central vision, due to the reduced spatial acuity and increased visual crowding in the periphery (Pilli & Tillman, 2008). In the context of the present study at least, it was imperative to control for task difficulty given that the previous three behavioural studies carried out showed a significant effect of task difficulty on overall target detection and discrimination. Therefore, the inclusion of noise was studied only in the behavioural study whilst ensuring that such effects did not confound the pure attention focusing capability with factors such as visual crowding (e.g. Martelli, Majaj, & Pelli, 2005) in the fMRI study.

  When considering dual face discrimination, that too in the context of face orientation, an important attribute worth familiarising is that of face inversion effect, i.e. the disruption of facial recognition due to inversion (McKone, Kanwisher, & Duchaine, 2007). Several neuroimaging studies have confirmed a greater response in the fusiform face area when presented with images of upright faces compared to inverted faces (e.g. Pitcher, Duchaine, Walsh, Yovel, & Kanwisher, 2011; Yovel & Kanwisher, 2005). According to previous suggestions, the face inversion effect is mainly due to the loss of stimulus (face) information regarding configuration when the faces presented to the participants were inverted (180°), a difficulty explained by a failure in employing specialised processing systems, i.e. holistic (perception based on distinct parts of the whole face: Taubert, Apthorp, Aagten-Murphy, & Alais, 2011) and configural (perception based on facial features: DeGutis, Chatterjee, Mercado, & Nakayama, 2012), concerned with perception of inverted faces. An alternative account of the face inversion effect comes from a difficulty in mental rotation of the inverted image (a processing stage which follows shortly after normalisation) whereby the configuration of multiple facial features gets weakened (Collishaw & Hole, 2002). Furthermore, a couple of recent studies demonstrated that more attention was allocated to inverted faces to the same extent, if not slightly lesser, concerning upright faces (Olk & Garay-Vado, 2011). However, the present behavioural study made use of the manipulation with face rotations carried out across multiple angles (e.g.

Collishaw & Hole, 2002; Rossion & Boremanse, 2008) rather than simply upright vs. inverted. Although studies in the past have demonstrated a mental rotation deficit in AwDys for letters (Rusiak, Lachmann, Jaskowski, & Leeuwen, 2007), to my knowledge not many studies have attempted to look at such effects with human face stimuli (with the exception of Moscovitch, Winocur, & Behrmann, 1997; Russeler, Scholz, Jordan, & Quaiser-Pohl, 2005). Nevertheless, given that AwDys found it difficult to exclude distractors (i.e. orienting Gabor patches) in the previous behavioural studies, the rotation of face stimuli gave the added flexibility to introduce varying levels of distractor free external noise, i.e. the noise caused by rotations.

6.3 Study Aims

The present study investigated:

- Whether AwDys (similar to controls) were able to modulate visual attention efficiently so as to narrow down their attention focus to aid detection and discrimination of the faces whilst ignoring the distractors.
- The extent to which face fusiform area activity would correlate with the behavioral measure of attention focusing for upright faces, compared to inverted faces.
- What was the cut-off angle of rotation at which recognition performance for faces reduced to chance level in AwDys, compared to controls?

6.4 Methodology

6.4.1 Preliminary screening

- Ethics - The current study was approved by the Department of Life and Health Sciences Research Ethics Committee (Aston University). All participants were subjected to a short session at the very beginning which described the risks, safety precautions, and the main procedures so that they knew what to expect in this particular research study.
- Risk Assessment – A comprehensive risk assessment was conducted initially prior to ethics clearance.

- Informed Consent - Processes leading up to the stage of obtaining informed consent from all participants were similar to that in the previous two studies (e.g. for study 1 see **section 2.4.2.2**). Just that in the present study the participants were required to provide their consent before commencing the MRI experiment (see **Appendix 9**). Participants provided informed consent which conformed to the procedures approved by the Aston University's Ethics Committee on use of human participants.

6.4.2 Standardised Screening Tests

All three assessments, namely language (e.g. WIAT–II Spelling, WIAT–II Word Reading, TOWRE-SWE and TOWRE-PDE), IQ (full scale), and an ADHD questionnaire were carried out similarly to that in study 2 (**section 3.4.3**). In addition to the above, participants were also tested on two extra measures, namely letter reading (letterchains test, LCT: Miller-Guron, 1999b) and word reading (wordchains test, WCT: Høien & Tønnesen, 1997), both which was intended to screen out any difficulties in letter and word recognition. The WCT in particular is believed to be a dependable screening measure for assessing reading impairments in dyslexia (e.g. Miller-Guron, 1999). The LCT served as the control for the WCT, with the former requiring participants to divide (by marking a border) 60 letters presented in chains into many groups as possible within the allocated 90 seconds. This was followed by the WCT, a test procedure which consisted of 400 words divided into three or four wordchains in a batch of 120, with participants required to identify component words (by making a border to divide up the words) within the allocated 3 minutes. All tests were administered according to the specifications instructed by the test manual.

6.4.3 Selection Criteria

Based on the language assessments, the selection criteria for the AwDys group was such that each participant showed: (i) a profile of enduring reading and spelling difficulties and/or previous clinical diagnosis; (ii) no symptoms of ADHD; and (iii) no symptoms of other neurological and/or psychiatric problems. The control group was required to have no previously reported problems in: (i) spelling or reading and (ii) symptoms of ADHD (although controls were screened just like AwDys – **section 4.4.3**). Participants in both groups were required to have a minimum full scale IQ of 90. Of the three (1 control and 2 AwDys) participants who volunteered for the study only two (1 male and 1 female) AwDys satisfied the inclusion criteria (M = 24.35, SD = 5.27). None of the two AwDys took part in any of the previous behavioural studies mentioned in this thesis.

6.4.4 Experimental Stimuli

This experiment involved looking at three types of stimuli, namely objects, faces and houses. Samples of the stimuli used in this experiment are shown in **figure 38**. Each stimulus was 300 x 300 pixels in dimension, either of grayscale or two-toned format. The 90 face images used in this work was obtained from the CVL Face Database, Computer Vision Laboratory, University of Ljubljana, Slovenia (Solina, Peer, Batagelj, Juvan, & Kovac, 2003). The 90 assorted images of common objects were obtained from Google, with picture editing performed using Gimp™ (version 5.0). The 90 images of houses were scanned from an architecture book. The type of stimuli being presented to the participants was dependent on the task type. On one hand, the localisation task consisted of alternating stimulus blocks displaying gray-scale images of faces and objects. On the other hand, the attention task consisted of stimulus blocks displaying two-toned images of faces and houses simultaneously.

6.4.5 Apparatus

The spatial cueing search task was developed and controlled by a P4-Dell™ Optiplex GX 260 desktop computer running using E-Prime 1.2 (Professional Version)™. The stimuli was projected at a resolution of 1024 x 768 pixels in 16-bit colour via a digital projector onto a translucent screen (36 cm in diameter) mounted to the rear interior of the scanner gantry. The participants were able to view the stimuli being presented to them through a set of mirrors secured to the head coil. The participants viewing distance was roughly 60 cm away from the translucent screen.

6.4.6 Design

This study comprised of two different experimental tasks, namely localization and attention, conducted during three alternating sessions using a conventional block design.

The localisation task (sessions 1 and 3) initiated the study whereby the main focus was to search passively for a specialised brain region within the ventral occipitotemporal lobe for each participant responding significantly towards images of faces than that of objects. Passive viewing of stimuli (grayscale faces and objects) was opted in this task, given the automatic nature of perception towards foveally presented faces, a process which was hard to control volitionally (Farah et al., 1995). The perception of non-face stimuli (objects)

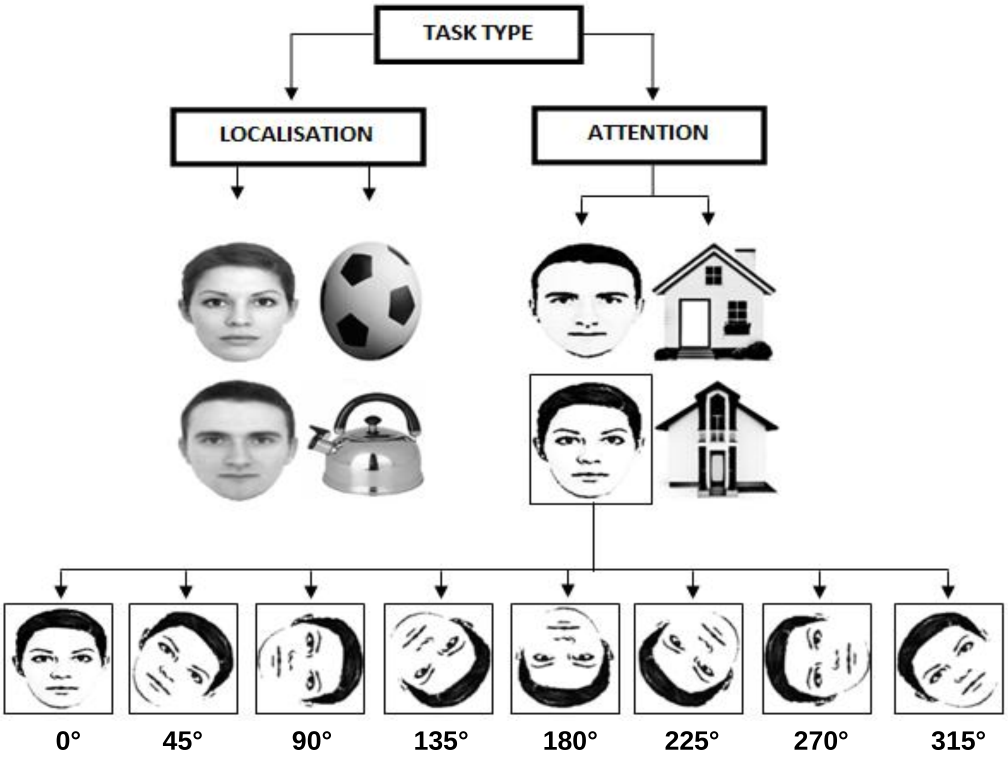


Figure 38: Stimuli types employed in study 4. The type of stimuli used was dependent on the task type. Stimulus for the localisation task (grayscale) was presented centrally, while the attention task had both faces and houses stimuli (two-toned, achieved by thresholding the grayscale images) presented peripherally. The latter was extended to a separate behavioural study whereby the face stimuli were of varying orientations (only one sequence of face orientations is shown here as an example).

served as the control condition. This localisation task served two crucial functions, firstly necessitating the location of candidate face areas, in addition to determining the region of constant activation (across all participants) so as to indicate the exact number of voxels to be used on a distinct brain region of interest (ROI) ahead of the attentional task.

The attention task (session 2) consisted of a different stimulus set, namely a pair of two-tone face and house stimuli. The use of two-toned, as opposed to grayscale stimulus format permitted better discriminability at the peripheral regions given that the attention study focused on detection and discrimination of a target amid distractors. In particular, the faces vs. houses stimuli manipulation was designed to test whether the FFA was involved in any form of object processing across different exemplars, apart from face perception. It is important to know that all facial features (e.g. hair, shape of the head) were similar in all exemplars, therefore recognizing the face on the basis of external features was less probable.

6.4.7 Procedure

6.4.7.1 Localisation Task

The localisation task consisted of six (3 each for faces and objects) stimulus epochs of 30 sec duration each, interspersed with seven 20 sec fixation epochs (**figure 39**). Stimulus epochs alternated between the face and objects conditions in such a way that the batch of stimuli used in the first stimulus epoch (face perception) were exactly the same for those used in the fifth stimulus epoch (face perception); the stimuli used in the second stimulus epoch (object perception) were exact as those used in the sixth (object perception). The stimuli used in the subsequent third (face perception) and fourth (object perception) epochs were from a fresh batch. Each epoch within the localisation task commenced with the appearance of a black fixation cross (**+**) against a gray uniform field for 17 sec. This was immediately followed by a 3 sec instruction screen informing the participants as to what stimuli were to be presented. During each stimulus epoch, 45 different stimuli (either faces or objects) were presented at the centre (15 x 15° visual angle) at a rate of one image every 670 msec (stimulus onset for the first 500th msec and offset for the remaining 170 msecs). The participants were not required to input any response, just that they were instructed to attentively view the stimuli presented to them under passive viewing conditions, whilst maintaining central fixation in addition to minimizing other mental processes being carried out simultaneously during the localisation task. Note that each participant went through two runs of the localisation task, once before and immediately after the attention task. An average of the two localisation tasks were then taken, given that a previous studies indicated a weak significance from a single run unlike when averaged across two identical runs (e.g. Kanwisher et al., 1997). Total duration per run was 5 min, 20 sec.

6.4.7.2 Attention Task

The attention, or otherwise known as the matching task, consisted of ten (5 each for faces and houses) stimulus epochs of 16 sec duration each, interspersed with eleven 6 sec fixation epochs (**figure 39**). Stimulus epochs alternated between the face and house conditions with each epoch having a fresh set of stimuli, so as to avoid participants from recognising potential target specific features from continuous exposure. Each fixation epoch commenced with a central fixation (**+**) against a gray uniform field of luminance 18 cd/m^2 for 3 sec. This was immediately followed by a 3 sec instruction screen informing the

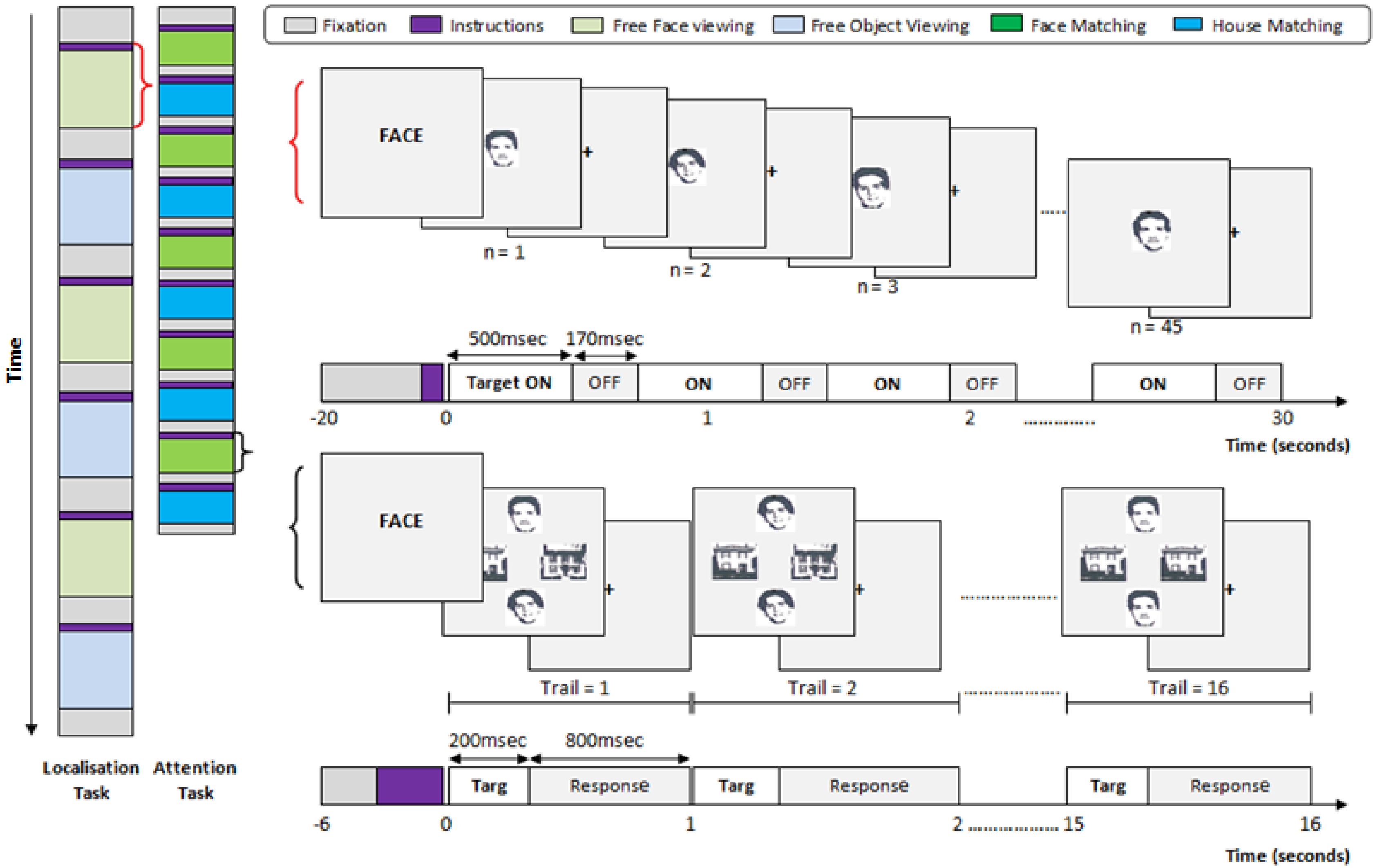


Figure 39: Display sequence of a typical trial for the localisation (upper panel) and attention (lower panel) tasks for study 4.

participants as to what stimuli were required to be matched (either faces or houses). In separate epochs, 16 different stimuli were presented at specified locations within the periphery. The spatial arrangement was such that a pair of face stimuli appeared vertically above and below central fixation, whilst a pair of house stimuli appeared horizontally to the left and right of central fixation, where each display subtended 25 x 20° visual angle. Each stimulus within an epoch was presented at the rate of one image every 1000 msec (stimulus onset for the first 200th msec and offset for the remaining 800 msecs), totalling 16 trials. The participants were required to firstly, match the concurrent target stimuli (e.g. faces) of varying orientations while ignoring the distractors (e.g. houses) and secondly, to report whether the given pair of target stimuli (i.e. in this case faces) were same or not (with 50% probability). Three separate runs of the attention task were carried out per participant. The matching conditions were in the order of F-H-F-H-F-H-F-H-F-H (where F refers to face, and H refers to house), with total duration per run being 4 min, 50 sec. Participants responded by making specific key presses on a standard two-key response box using their dominant hand.

Although eye movements were not monitored in this study, the current experimental paradigm had a couple of strengths to negate any confounding sensory factors. Firstly, participants were expected to fixate at the central fixation cross whilst covertly attending to peripheral locations only when specified. Second and most importantly, even if participants attended the peripheral target overtly, it would only be to their disadvantage given that 200 msec was way too quick to consciously deploy saccades during the search process. Furthermore, by having the eyes fixated at the periphery rather than at fixation, it only made target detection harder, since focusing on one given target stimulus of a pair made the other detectable to a much lesser degree.

6.4.7.3 MRI Data Acquisition

The MRI recording was performed using a standard birdcage head coil on a Siemens™ 3T-Trio Magnetic Resonance Imaging System, housed within the Aston Brain Centre, Aston University. During each anatomic and functional scan, a series of brain volumes within the right fusiform gyrus was acquired via an echo planar imaging pulse sequence bearing the following scan specifications: TR = 2.8 sec, TE = 30 msec, flip angle = 90°, with 180° offset = 22 msec, 38 slices, slice thickness = 3 mm, voxel size = 4.75 x 3 x 3 mm, matrix = 64 x 64, 192 mm field of view, and bandwidth = 752 Hz/Px.

6.4.8 Behavioural Study

The aforementioned paradigm was extended to a behavioural form with a few minor changes. The research question of interest remained the same as that for the fMRI study, i.e. the extent to which participants were able to exclude noise (distractors). However, the behavioural study assessed noise based on a face rotation set-up. The stimuli which were presented varied in orientation based on four different configurations (**figure 38**): upright and inverted (0° and 180°), right and left (90° and 270°), diagonal left (135° and 315°), and diagonal right (225° and 45°). The noise to which the participants were subjected was entirely dependent on the extent of face rotation, with less noise for upright (0°), higher noise for inverted (180°), whilst increasing linearly with the angle of rotation between the two items (45 - 135° and 315 - 225°).

Figure 40 illustrates the sequences that took place in a single trial. Each trial sequence commenced with a gray uniform screen (luminance 18 cd/m^2) with a central fixation (110 msec) initiated by a key-press. This was followed by a blank fixation screen (110 msec) containing a rectangular placeholder indicating the configuration of the paired stimuli (identical or different two-toned face stimuli of the same orientation) to be presented (i.e. horizontally or vertically on either side of fixation). Shortly afterwards, a stimulus display (variable duration, and calibrated similar to studies 2 and 3) corresponding to either one of two configurations (as previously indicated by the placeholder) was presented, followed by a blank fixation screen (3000 msec). The participant responses were based on whether the two face stimuli were identical (key-pressing "Z") or different (key-pressing "M") with 50% probability. A response reminder screen was presented there after (i.e. if no responses were entered within the allotted time) reminding the participants to do so. The response accuracy provided a measure of the participant performance across conditions. This experiment provided a measure of how well AwDys, compared to controls, were able to exclude noise at the periphery in contrast to that at the central focus (fMRI task). In total, ten blocks comprising of 48 trials each were run for the main experiment (in addition to shorter practice sessions), requiring roughly 20 - 25 minutes in total for each participant.

6.4.9 Data Analysis

The initial pre-processing of raw data was carried out in SPM5 (Aston Brain Centre - Imaging Suite, Aston University). The first step of data analysis was to fit each participant’s high-resolution anatomical and function data to their respective Talairach

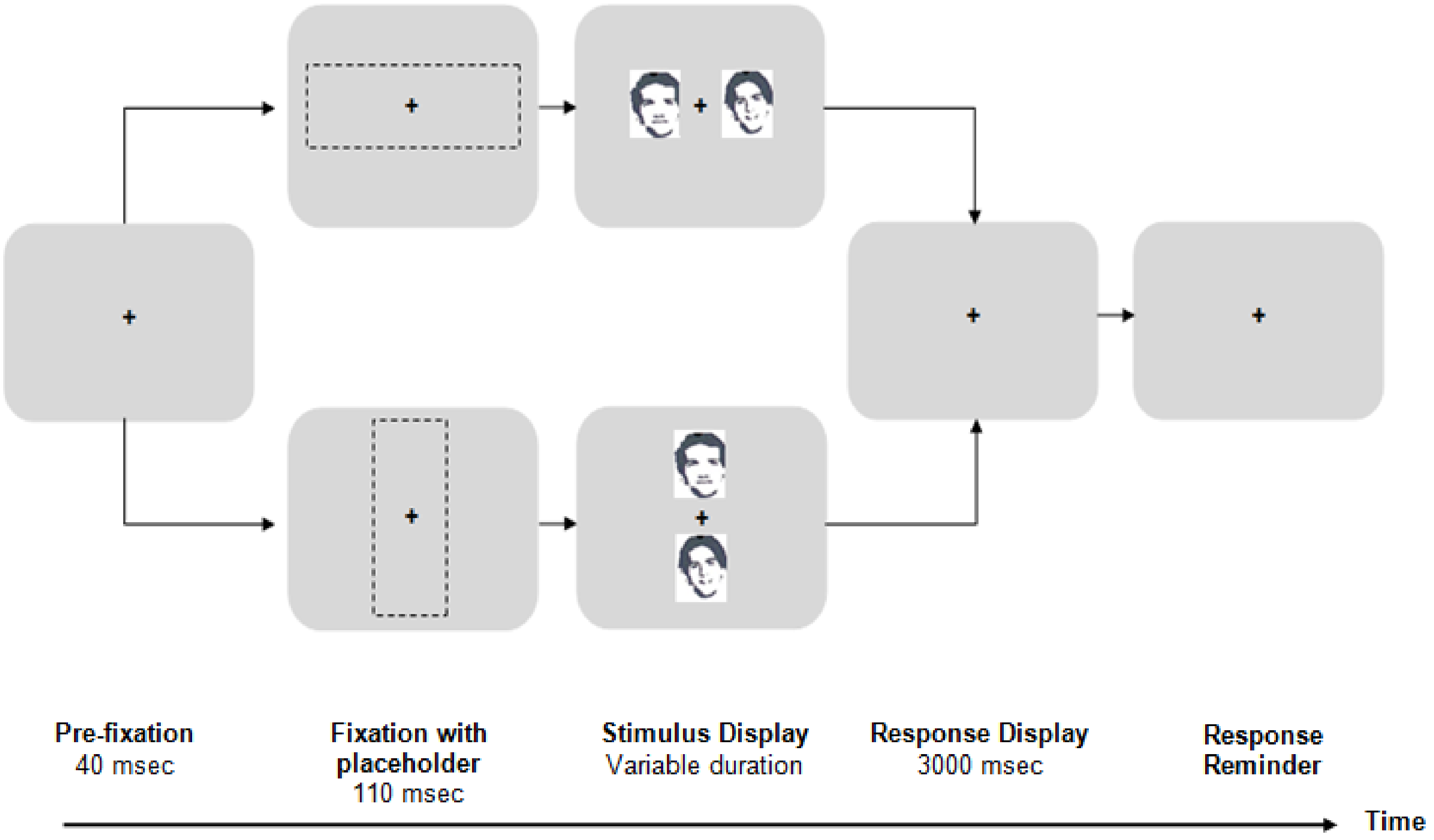


Figure 40: Schematic sequence of the behavioural search experiment in Study 4. The variable duration display with a 50% probability of (i) any one of the two stimulus display type's from occurring, and (ii) any two face stimuli to be identical, at a given trial. Note, the faces presented on either side of fixation were of the same orientation, with possibilities ranging between 0, 45, 90, 135, 180, 225, 270, and 310° (perfectly upright face shown as an example). Two-toned face stimuli were utilised.

atlas, closely followed by analysing specific brain regions which produced the greatest signal upon detection of the face (compared to the object) stimuli. Based on the ROI sampled, a couple of pilot scans carried out on control participants confirmed the location of significantly greater activation (i.e. a minimum of two contiguous voxels responding more strongly to faces compared to objects at $p < .001$) to be the right fusiform gyrus. The next step in line was to calculate the average across all the voxels in each participants predefined face ROI (from the localisation task) in order to obtain their raw time course of signal intensity specific to the pre-sampled ROI. For this to happen, the data from the attention task was initially averaged across three runs, followed by averaging that for all voxels within each participants pre-defined ROI. For each participant, the percentage signal change was then calculated (separately for face and house matching epochs) from the signal intensity specific to each participants face ROI by averaging the signal specific to face and houses across all the fixation epochs (i.e. baseline measure). This analysis was performed by carrying out separate t-tests (based on the percentage signal change) to compare the five epochs concerned with face matching to that of five house matching (for each participant). The output from the aforementioned batch of analysis should give a direct measure of distractor exclusion based on the activation within the FFA, whilst ignoring the noise (distracting house stimuli), thus explicitly approximating how well attention was modulated.

The key piece of analysis would be to take each control participant’s response in the FFA for face matching vs. house matching, and subtract one from the other to arrive at the difference in the percentage signal change. Using this subtraction method, one could assume controls to have quite a significant net activation. When comparing this with participants with dyslexia, the opposite is what is speculated with the amount of activation being significantly smaller or null all together. Should this be the case, it further complements previous findings (from studies 1, 2 and 3) thereby confirming poor attention modulation in dyslexia, i.e. an inability to narrow down the focus of visual attention.

Unfortunately, that is as far this study progressed given the unexpected circumstances:

- difficulty in recruiting AwDys volunteers from Aston University (the period during which testing took place also coincided with peak exam and holiday periods).
- although two AwDys underwent the fMRI scan sessions, scans from both these participants indicated significant head movements. There were no data from controls to draw any between group comparisons.
- although a handful of other AwDys signed up to take part in this study, all if not most showed contraindications for scanning following preliminary MRI safety screening.

Chapter 7:

General Discussion

7.1 Research Theme

One crucial function of visual attention is based on the initial splitting of the relevant signal from the irrelevant (noise), followed by the filtering of noise from undergoing further processing. The three behavioural studies based on this thesis concentrated chiefly on covert spatial attention and its potential role when filtering external noise in conditions where both target and external (distractor) noise co-occurred in space and time (similar to those carried out previously by Facoetti et al., 2010; Roach & Hogben, 2007; Sperling et al., 2005). By manipulating the degree of external noise (variations in display set-size), the task specific modulation of visual cues (pre, post and un-cues) and task demands (a variant of perceptual load), it was possible to determine the three categories of attention mechanisms (signal enhancement via pre-cueing, external distractor noise exclusion via post-cueing, and internal/decisional noise reduction via search vs. non-search), in addition to working out the changes in perceptual discriminability achieved by both controls and AwDys. This gave us the platform from where it was possible to determine as to how strong an association these deficits had with reading performances by the AwDys. Furthermore, attempts were also made to categorise the present adult dyslexic participants based on subtypes. The paradigms employed throughout the three behavioural studies are novel, in that we were able to simultaneously investigate a set of attentional functions for which individuals with dyslexia were known to suffer from. These paradigms also in many ways overcame some of the confounding factors from previous studies (e.g. Martelli et al., 2009 on crowding; Roach & Hogben, 2007 on attention functions). In this way, we were able to arrive at a conclusion as for the extent to which individuals with dyslexia (adults) were able to modulate their attention.

The following few sections shall focus on the key findings based on the studies carried out and discussion of how these findings tally will the current literature. The sections to follow also provides a discussion of the importance of these findings in terms of its contribution to the field of dyslexia and how such findings are currently opted to provide remediation’s to individuals with dyslexia.

7.2 Reflection on Key Findings

7.2.1 Attention Orientation and Visual Crowding

Studies 1 (**Chapter 2**) and 2 (**Chapter 3**) simultaneously investigated the effects of cueing, task difficulty and spacing factors between a group of AwDys and adult controls (not matched for age or IQ) whilst efforts were put into place to control for overall performance levels between the two groups. The preliminary study showed that AwDys, when compared to controls, had decreased performance when distractors were placed closer together, in addition to them being able to successfully utilise the target pre-cues (better than the post-cues) to enhance the target signal so as to overcome the detrimental effects of crowding especially when the displays were un-cued. In other words, AwDys were able to ignore the crowdedness using the pre (and post) cue, which goes to show that attention screens out the noise effectively thereby relieving crowding. In line with Sperling et al's (2005) proposal of dyslexic individuals being unable to exclude noise, our initial investigations using a crowding manipulation suggests that AwDys are better at excluding noise at an attention level (with the help of pre-cues, Roach & Hogben, 2007) rather than at a decisional level (with the help of post-cues) crucial for the enhancement of the target surrounding the distractors. Findings from both these studies are also consistent with a significant crowding effect as previously observed in other crowding studies (e.g. Scolari, Kohnen, Barton, & Awh, 2007; Spinelli et al., 2002; Strasburger, 2005; Yeshurun & Rashal, 2010).

The observed crowding effect in the current set of behavioural studies carried out is attributed solely to an influence of attentional, rather than linguistic factors, given the use of simple non-linguistic stimuli. However, despite efforts to ensure that any variability in performances was independent of individual differences in stimulus discrimination (via means of detection accuracy calibration), the overall performance of AwDys was lower than that of controls. This happened to be the case even during the pre-cued spread conditions, with the expectation that AwDys would perform equally to controls given that the average display duration for the AwDys was significantly longer than that of controls [i.e. 176 msec vs. 92 msec, $t(31) = 10.837$, $p < .001$]. Nevertheless, the statistical approach by having partitioned the analysis in a group-wise manner (so as to compare selective rather than the entire performance across experimental conditions) did bring forth one possible constraint thought to have evolved from dissimilarities in discrimination performance. That is, whilst the stimulus display was un-cued, both controls and the

AwDys showed a notable dissimilarity based on the pattern of results across both the spacing conditions. Furthermore, the task difficulty seemed to generally affect AwDys especially when the stimulus array was both post and un-cued. Therefore, the comparably larger crowding effect during easy task discriminations indicates the fact that discrimination ability is not the most important mediator of the crowding effect as observed in AwDys (Ramus & Ahissar, 2012).

Studies in the past have accounted for various effects of crowding in dyslexic individuals (Bouma & Legein, 1977; Pelli et al, 2007; Martelli et al., 2009; Pernet, Valdois, Celsis, & Démonet, 2006) but much of this has been explained in terms of deficient spatial resolution of visual attention (Intriligator & Cavanagh, 2001). It suggests that the extent of crowding is determined by the minimal selection region of attention. When more than one item fall within the smallest possible selection region of attention, the items are selected as a group, and there is no access to the individual identity of one item. In this case, the identification of an individual item is not possible as a constant number of distractors were present during the spacing manipulations I both studies 2 and 3. Moreover, the minimum spacing between the stimuli in this crowding manipulation (1.6° of visual angle) was larger than the estimated space needed for attention to prevent distractors' interference (1° of visual angle), the latter shown by the work of Murphy & Eriksen (1987). According to this view, crowding reflects the limitation of the spatial resolution of attention. Since the selection mechanism attracted by the pre-cue is the same mechanism that selects the item for final identification, our current results do not support the attention resolution theory because directing attention to the pre-cued location reduced the extent of crowding. That is, crowding was not limited by the attentional selection and this meant that attention enhanced the processing capability at the focus of attention leading to a more distinct representation of the target.

Nevertheless, the findings from study 3 (**Chapter 4**) helped clarify the crowding deficit even more vividly. Similar to studies 1 and 2, AwDys demonstrated a significant crowding effect in study 3 even when the decisional uncertainty was brought down to its bare minimum on a ratio of one in eight (study 2) is to one in two (study 3). One explanation for these findings in individuals with dyslexia is the possibility of reduced visual attentional resources which thereby serves to limit the quantity of characters being processed within a single glance (Romani et al., 2011). Nevertheless, the performance of AwDys in both studies 2 and 3 reflects a marked difference when compared to controls, despite subjecting the participants’ with stimulus displays with varying stimulus spacing’s independent of display set-size. On one hand, by opting to the stance taken by Romani and colleagues (i.e. given the components of the display are processed regardless of the location), it could mean that the observed crowding effects in both studies 2 and 3 happened to be totally independent from the distribution of visual attention. On the other hand, in accordance with the attention spotlight model, a highly diffused mode of attentional distribution in dyslexic individuals (e.g. Facoetti et al., 2001) is more likely to bring about a significant crowding effect similar to that found at distant target eccentricities. Moreover, the finding from the present study that pre-cueing target location improved overall detection and discrimination accuracy in AwDys is consistent with findings found within control populations (e.g. Scolari et al., 2007; Yeshurun & Rashal, 2010), the latter revealing that attention could also serve to reduce the critical distance for accurate detection of targets among distractors. Therefore, the crowding effect in AwDys from the present thesis is in agreement with a more diffused mode of visual attention (e.g. Facoetti, Paganoni, & Lorusso, 2000; Facoetti et al., 2001; Turatto et al., 2000), in addition to a diminished visual attention span (e.g. Bosse et al., 2007), on conditions that both these models are connected to a separate, besides a analogous aspect of visual crowding.

7.2.2 Attention Distribution and Focusing

Diffused attentional resources (e.g. Facoetti, Paganoni, & Lorusso, 2000a; Facoetti et al., 2000b) can be explained in terms of difficulties having to narrow down the attentional focus (e.g. Facoetti et al., 2001; Valdois et al., 2004). When the attention spotlight is spread, target search may be conducted in parallel across all items in the visual field at the expense that an irrelevant distractor would also be selected automatically. In study 2 (**Chapter 3**) at least, it seemed that AwDys (similar to controls) were able to narrow their attention focus to a minimum such that the irrelevant distractors that fell outside of the attentional window did not capture attention (see **figure 41**). However, in study 3 (**Chapter 4**) where no search process was required, one would expect that with such a narrowed attentional spotlight especially in a crowded stimulus display, the irrelevant distractors that fell inside the spotlight would result in attention capture but not in the spread condition. In study 3, a considerable difference was evident between both groups in the left visual field despite it being a non-search task with a requirement of serially focusing the attention spotlight across the stimulus display. Here, not only did AwDys commit more errors overall in the left visual field than control group, but the ability to detect the presence of a target gradually decreased with increasing set-size. However, no similar gradual decrease in the discrimination accuracy was observed for the control group, with their performance being constant overall despite minor fluctuations. The finding that the performance of AwDys and control groups was almost identical for the zero display indicates that AwDys had no problem in shifting their attention between the left and right visual fields. Similarly, the performance between AwDys and control groups was not significantly different with the two-item (spread) displays, indicative of the fact that AwDys were efficient at performing the actual (fairly difficult) task of excluding noise from the irrelevant stimuli, which required both shifting and refocusing the attentional spotlight. It should be noted that this increase in display set-size not only meant increased noise levels due to the competitive nature of the neighbouring distractors, perhaps it could have also given rise to an increased stimulus density on a given VF to which the stimuli was presented. Therefore, the finding that the performance of the two groups began to diverge at the four-item display level and diverge substantially more at the eight-item display level suggests a weaker functioning of the attention system as the displays became more both noisier and denser. That is, AwDys encountered a major difficulty in further narrowing down the attentional spotlight to a more restricted area in the visual periphery (which happens to be on the left visual field) in order to selectively process the only target available at any given time while excluding the interference of neighbouring items, the features which could have signalled the wrong response. Clearly, these results point to a major obstacle for participants with dyslexia portraying an inability to restrict the attentional spotlight, in addition to the poor noise exclusion, and thereby confusing the identity of the target and adjacent distractors.

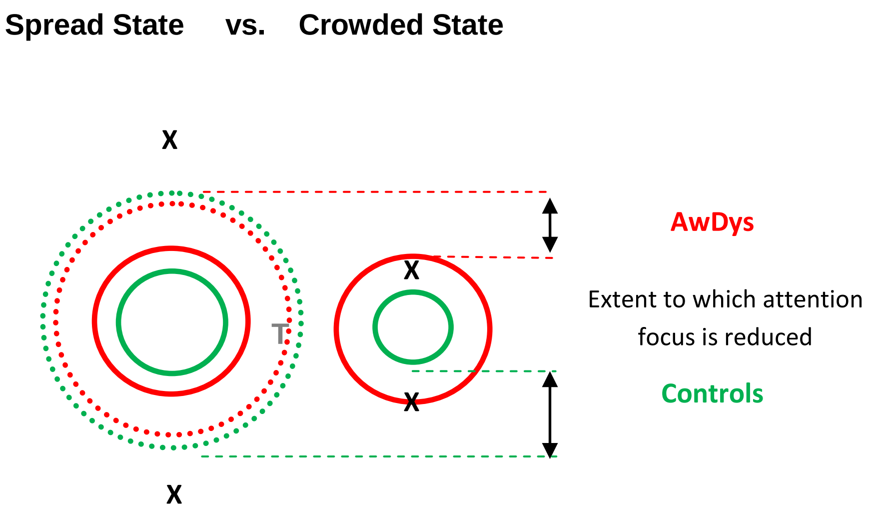


Figure 41: Comparison of the reduction in attention focus between controls and AwDys. While controls were able to modulate their focus of attention from a maximum position (dotted green) to minimum (solid green) in both spacing conditions, AwDys weren’t as flexible when it came to reducing their focus to the minimum required in order to exclude the closely crowded distractors.

The detection and discrimination task used in the current study in addition to some of the previous research (e.g. Facoetti et al, 2000a) ensured the need for participants to vary the size of the attentional focus across both the visual fields. The size of the attentional focus that can be reduced to, and maintained at, was not only affected by the ability to filter the distractors that surround the target, but it could have been also affected by the degree of task difficulty (perceptual load). This suggests that the disruption to efficient target detection and identification in the periphery was further modulated by task difficulty in AwDys. With increasing task difficulty, for a target stimulus presented on a display which operates independently of search, the effect of surrounding distractor(s) was reduced. These findings are fully consistent with the idea that, when search becomes more difficult, the attentional window needs to be smaller/more focused resulting in a reduced effect of the irrelevant distractors that surround the target (see also Lu & Han, 2009). However, when attention is spread/more dispersed, visual search may be conducted in parallel across all items in the visual field, at the expense that an irrelevant distractor(s) would also be selected automatically. That is, when the attentional window is set to a smaller size, irrelevant distractors that fall outside of the attentional window will not capture attention. Since, attentional resources would be more concentrated in a narrow area than in a wide one, the smaller the focus the higher the speed of processing within its borders.

In addition to the above, what is important to understand is the impaired ability of AwDys to flexibly modulate the size of their visual attention span (as previously demonstrated by Bosse et al., 2007) in order to optimally allocate their visual attention in accordance with the above mentioned task demands. A diffused mode of attention, as proposed by Facoetti and colleagues (e.g. Facoetti et al., 2000, 2003) explains the comparatively larger effects of crowding in un-cued conditions observed both study 2 and 3. Such capacity limitations might apparently make it impossible for AwDys to monitor all the potential targets efficiently even under varying set-sizes, instead causing them to react by virtually neglecting certain target positions at the expense of others even when the uncertainty was at its bare minimum. However, one needs to take into account the differences in the two experimental paradigms used and the relative strengths it poses. Facoetti & Turatto (2000) opted to present the target centrally with the just the flanker presented in the left visual field, unlike the present study where both the target and distractors were subjected simultaneously on the left visual field. Facoetti & Molteni (2001) attributed this attention imbalance according to the observations they made based on the performance over a particular VF. They suggested an inattention deficit on the left-VF to explicate the overall slower responses, with over-distractibility on the right-VF to describe the deficiency of a performance gradient traversing from central (endogenous) areas towards the periphery (exogenous). Moreover, Waldie & Hausmann (2010) reported a complete turnaround of the standard leftward bias in both CwDys and in children with ADHD when observed using a line bisection task.

Nevertheless, the crowding effects demonstrated in the current batch of studies are in line with earlier proposals using a variety of stimuli (Spinelli et al, 2002; Pelli et al., 2007; Martelli et al, 2009) which show a strong link between crowding effects and poor reading performance in dyslexia. For instance, Spinelli et al (2002) demonstrated that CwDys displayed longer reaction times to process both letters and letter like symbols in the presence of surrounding stimuli unlike when presented in isolation. Also an increase in inter-letter distance was reflected by shorter reaction times in CwDys. Whilst Pelli et al (2007) was able to closely relate both crowding and reading rate in normal readers, Martelli et al (2009) extended this study further demonstrating a strong correspondence in CwDys between crowding and reading rate. Martelli et al (2009) found that Italian dyslexic children performed equally as well as controls when identifying a single target letter, but needed greater spacing than controls for identifying a target letter surrounded by two other distractor letters, and they concluded that "word analysis in dyslexics is slowed because of greater crowding effects, which limit letter identification in multi-letter arrays" (p. 1). This goes to show that crowding can hamper efficient reading capability in individuals with dyslexia whilst reading a letter from a word (Blau et al., 2009) or word from a sentence (Ziegler et al., 2010).

7.2.3 Distractor Exclusion

Having found that the noise exclusion deficit at a (late) decisional stage was responsible for diminished performance across crowded displays, we were also keen to investigate whether this was the case across the entire search function, especially when targets were presented at high noise (set-size) conditions. Findings from study 2 (**Chapter 3**) showed that AwDys were able to make good use of pre-cues, albeit they suffered more than controls at set-size 16 given large number of distractors present within the search array (**figure 28**). This was quite the same even when the target was pre-cued, especially when the task discrimination was difficult. Moreover, we found set-size effects for controls to be a touch significant across all the cue conditions, nevertheless it was predominantly significant for AwDys. Most crucially, although the cueing advantage was observed in the control group (i.e. both pre and post-cues eliminated effects of set-size), however this was not the case with AwDys with the latter having performed significantly worse at high external noise (i.e. at larger stimulus set-sizes, 8 and 16 specially) regardless of the type of informative cues (pre and post) presented to them. This finding is also common with some studies having showed differences in cueing benefits between controls and AwDys (Facoetti, Paganoni, & Lorusso, 2000) while other studies did not (Buchholz & Aimola Davies, 2005, 2008; Roach & Hogben, 2004). Nevertheless, the current findings support the external noise exclusion hypothesis which speculates that AwDys have a general deficit in filtering out irrelevant information when attending to a target signal of interest (e.g. Sperling et al., 2005).

Nonetheless, this viewpoint does not clearly elucidate the differences in performance as observed in an un-cued state (studies 2 and 3). That is, each stimuli being presented within the sixteen maximum locations available on an un-cued stimulus display turns out to be a potential target, with harder orientation discriminations instilling further attention demands. Therefore, the problem with AwDys may potentially come down to a greater overall difficulty with the (detection and discrimination) task at hand given the added perceptual load. It therefore becomes paramount to deduce the extent to which un-cued distractors interfere with search performance and the best way forward would be to reduce the load. In an attempt to reduce the perceptual load present within the paradigm (i.e. reducing the set-size from one in sixteen in study 2, to one in two in study 3), the findings from study 3 still for all demonstrated reduced search performance in AwDys when search displays were un-cued. With the un-cued distractor stimuli interfering search performance in AwDys especially at set-sizes 4 and 8 (**figure 34**), initial observations reflected a potential weakness in the adult dyslexic participants' ability to filter noise altogether. This makes sense to some extent due to the concomitant influence of decision effects (spatial uncertainty) where irrelevant information from multiple non-target locations is expected to increase the possibility of false alarms (e.g. Dosher & Lu, 2000).

Particularly relevant from both our studies is the question, what makes un-cued distractors to be inefficiently excluded by AwDys? First, according to the limited capacity theory, a minimum amount of attentional processing is a requirement for detecting and discriminating a target from the distractor. Here, the quality of attentional processing is maintained as the set-size increases, however, performance declines because the presence of distractors gradually exhaust the attentional resources and increases the number of errors occurring at the decision level, resulting in lower performances. Underlying this theoretical stance, the set-size effects suffer in the face of spatial uncertainty regarding the location of a target. That is, when the location of the target is known in advance (for instance with the help of pre-cues as utilized in our previous study), there would be no need to distribute attentional resources over the entire stimulus display or to serially shift attention between multiple-display items (target + distractors). Stimulus detection and/or discrimination under such conditions of known target/spatial position should therefore be unaffected by the increasing display set-size. These findings are in close agreement with our view that decisional noise affects sampling efficiency, and therefore disrupts a common attentional resource deployed for both processing of targets and distractors.

When comparing the severity of un-cued displays (in both the current and previous study) to post-cued displays (from our previous study), despite the presence of decisional noise in the latter, AwDys weren't able to overcome the set-size effect even when the facilitation of noise exclusion was accounted for. It is valid to note that suppressing the strength of distractors can take the form of a change in decision criteria, which necessitates the observer to weigh visual information from different input sources (Chen & Tyler, 2010). In general, decision based explanations of attention argue that spatial attention allows the observer to exclude distractors that differ along some relevant dimension from the input signal by narrowing a 'filter' that processes the stimulus. In essence, distractor suppression is thought to be an external noise reduction mechanism which operates via a decision factor based around feature differences between target and distractors. Although our current study minimized both the spatial uncertainty and the noise levels considerably with noise exclusion mechanism solely at stake, AwDys were still unable to overcome the set-size effect. This in itself point towards a possibility that individuals with dyslexia despite their ability to orient their attention accordingly (i.e. no problem with target detection as shown in our former study), they do seem to filter out too little of the distractors that surround the target. Therefore, this may possibly result in a degree of unfiltered noise to coexist along with the target signal causing the observer to be confused when discriminating a potential target.

Second, the question of whether un-cued distractors interfere with performance on the relevant target stimulus is tightly related to another question: to what extent are un-cued stimuli actually processed? This question has been difficult to answer for at least two reasons. On one hand, in experiments demonstrating that un-cued distractor stimuli interfere with performance on the relevant stimulus, it is possible that such findings simply reflect weakness in participants' ability to ignore distracting stimuli (noise exclusion deficit: Sperling et al., 2005 and 2006) as mentioned above. On the other hand, even when un-cued stimuli do not interfere with performance (Roach & Hogben, 2004; 2007), this alone cannot be taken as evidence for incomplete processing since un-cued stimuli may be fully processed yet not considered in the decision process, as may be the case in both our experiments.

Third, although our former study showed differences in performance in AwDys between pre-cued easy vs. difficult conditions (in set-size sixteen displays), the set-size effect observed in the current study was pronounced only in the harder conditions. This result suggest that although the difficulty of our discrimination task in our current study (compared to search task in the former study) determines performance slopes, a significant slope do not always indicate the presence of an attentional capacity limit. A previous study carried out using a feature conjunction discrimination task have certainly shown little attentional capacity limitation even when the task was very difficult (Pernet et al., 2006). It seems, therefore, that attention capacity is not affected by search task efficiency, but is rather determined mainly by the nature of the task itself. That is, limited-capacity processing that is fast and efficient in easy non-speeded tasks, when faced with harder tasks, may become inefficient and inaccurate, but it still fails to show an attentional capacity limitation. For instance, when comparing group performances in studies 2 and 3, what started out with a deviance in the set-size one display in the former study, none so was evident in study 2 even at set-size zero. This points to a possible influence of an attentional capacity limit determined by task difficulty (performance slope) in a highly non-linear fashion. Perhaps we see no improvement in both the studies 2 and 3 only because AwDys efficiency is less than some threshold reflecting the point where attentional capacity limits come into play. Therefore, the task of discrimination might have no attention capacity limit when the set-size is smaller than a threshold, but still show attention capacity limits when the set-size exceeds that threshold (see, e.g. Pashler, 1998, for a related suggestion). The current results may be explained by assuming that the threshold is less than or greater than set-size 4 to differentiate between greater vs. poor spatial-discrimination capabilities in AwDys. Nevertheless, all of the above points taken together, a noise exclusion deficit in tandem with an asymmetric attention distribution stand out with regards to the observed deficits in the adult dyslexic group.

7.2.4 Impact of Attentional Deficits on Literacy Performance

The relationship between effects of cueing, crowding, set-size, asymmetry and measures of literacy achievement was further explored between AwDys and controls. The computed summary variables in association with reduced performance in crowded and larger set-size conditions correlated with lower literacy scores (WIAT-II spelling, word reading and TOWRE-PDE. The correlations found in studies 2 and 3 between reading ability and the ability to perform well with larger set-sizes, in addition to visually crowded conditions is in strong agreement with previous research. For instance, poor readers performed significantly worse than the non-impaired readers on the letter detection task only in the high external noise conditions, regardless of stimulus set-size (Beattie et al., 2011). Similarly, Sperling et al (2006) also reported a correlation between reading ability and ability to detect motion stimuli from noise. Furthermore, Martelli et al (2009) found a strong correlation between a measure of letter crowding and reading rate in Italian CwDys. Moreover, the current studies further proposed that AwDys have impairments in their ability to restrict their attention to a limited area on the left-VF when asked to respond selectively to a potential target surrounded by nearby distractors which again correlated with lower literacy scores when concerning the dyslexic group. To that end, Bosse et al (2007) identified an association between reading performance and a visual attention span measure. Moreover, Facoetti & colleagues (2006), found a strong correlation between visual-spatial attention and non-word reading accuracy.

How can the present findings be related to the reading problem manifested by individuals with dyslexia? At least based on the framework of the multi-trace model of reading, this might represent a difficulty in narrowing the visual attention span leading to a reduced ability in being able to read nonwords. By inferring the present behavioural findings to reading deficits in dyslexia based on this framework, it seems like the visual information presented in the left-VF in an un-cued display is not attuned efficiently enough to process a letter and/or word efficiently. Furthermore, the ability to filter out the noise from the signal flanking the attended area would be crucial especially when unfamiliar words have to be identified. It can be stipulated that this noise exclusion mechanism could be particularly defective in the left visual field in individuals with dyslexia, who without doubt be distracted when reading letters/words to the left from fixation. Moreover, visual-spatial attention is known to be more important for nonword reading compared to normal word reading. Therefore, despite this asymmetric attention in dyslexic individuals, attention is more focused in the right-VF in accordance to Facoetti et al (2006) which means they are deprived of the cueing effect in the right-VF which could affect grapheme-to-phoneme conversion process. It can be speculated that this left inattention might further affect the reading process in CwDys by resultant deficits with regressive saccades involving rapid backward eye movements involved in reading.

However, it is difficult to draw strong conclusions from certain outcomes given its novelty. Surprisingly, findings from study 2 demonstrated that AwDys were able to make good use of pre-cues, and that extent of cue use correlates strongly with reading and spelling ability, a finding which is unlike what many other studies have shown in the past (e.g. Facoetti & Molteni, 2001). One possible interpretation for the poor reading in the present sample of adult dyslexics comes down to poor detection and discriminatory performance involving a visual search task hampered due to a deficit in the attention focusing capability (Morris & Rayner, 1991). However, the findings from studies 2 and 3 demonstrate an intact attention orientation function in AwDys, with just the cue usage (dependence) influencing poor literacy. Any impairment in the ability to focus attention leads to poor suppression of adjacent letters when focusing at each successive letter in a word (e.g. Zorzi et al., 2012). A broader and weaker spatial window of attention could infer the difficulties AwDys come across when a crowded visual display is presented to them (e.g. Facoetti et al., 2000; Romani et al., 2011). Suppose this spotlight turns out to be weaker and broader compared to that of control participants, then distractors present at the periphery may not be fully excluded resulting in visual confusion. Given that studies have previously demonstrated negative correlations between the precision of nonword reading and the cueing effect observed on the right visual field (e.g. Facoetti et al., 2006), it is logical to consider that any difference in correlations could be attributed to the overall variations in the search task. For instance, the present study required participants to detect and discriminate a single target from varying number of distractors, while in the case of Facoetti & colleagues (2006) it came down to simply detecting a single target dot in the absence of distractors.

Nevertheless, the findings from the current behavioural study provides indirect support towards the hypothesis that poor readers with phonological difficulties have difficulty in analysing component parts of a word, i.e. in reducing their attentional focus. Direct evidence has been presented by Zoccolotti et al (2005) where good and poor readers were equally able to process words holistically whilst poor readers were less able to constrain their attention on word composition. Studies such as those conducted by Spinelli et al (2002), and Martelli et al (2009) just goes to show how crowding effect impacts negatively on reading performance. Interestingly, some studies have extended these findings towards manipulating the physical properties of print to offer some form of remediation to further aid and improve reading in dyslexia. One key property of print focused of recent times is the inter-letter and/or inter-word spacing (e.g. Perea et al., 2012; Zorzi et al., 2012). For instance, Zorzi and colleagues demonstrated an improvement in the text reading ability in a sample of Italian and French CwDys simply brought about by increasing inter-letter spacing thereby enabling the dyslexics to successfully counter the exceptionally strong crowding effect. Thus, the crowding effects observed in all three studies signifies the idea of visuo-spatial attention deficits where dyslexic individuals have a persistent impairment in the ability to focus on a given target (the successive letters in a visually-presented word) while suppressing the influence of the neighbouring distractors (adjacent letters in standard print). Given that the neighboring letter features add a certain weight to the perception of the focused letter, increasing the spacing between letters should therefore reduce the interfering effect caused by visual crowding, thereby allowing dyslexic individuals to effortlessly focus their visuo-spatial attention to recognize each successive letter within the word.

7.2.5 Dyslexia Subtypes

Using a selected batch of behavioural studies carried out, one further aim of this thesis was to deduce the relevance of reading profiles to identify heterogeneous subgroups of dyslexic adults. The findings from the initial set of analysis (**section 5.3.4**) demonstrated the absence of a double deficit within the AwDys group compared to the controls. However, the findings provides support for the presence of distinct subtypes in AwDys, with a majority of dyslexics exhibiting a single attentional disorder (62%), with the remainder exhibiting a single phonological disorder (32%). These findings were crucial in that, adult dyslexics with different reading profiles still go undetected when analysed as a group, rather than on a subgroup level, thus forming a heterogeneous population concerning a given cognitive disorder. The absence of such a double deficit in dyslexia is not entirely novel (e.g. Bosse et al., 2007; Dubois et al., 2010; Valdois et al., 2004), although recent neuroanatomical evidence describes the entire opposite (e.g. Norton et al., 2014). Nevertheless, the point worth nothing here is that the double deficit for findings based on this thesis applies solely to individuals with dyslexia showing both visual attentional and phonological deficits (e.g. Bosse et al., 2007), and not deficits related to phonological awareness coupled with RAN (e.g. Wolf et al., 2002).

The findings based on the second set of analysis (**section 5.3.5**) were that of dyslexic subgroups exhibiting different cognitive deficits associated with literacy measures when compared to controls. That is, on the whole, the observed phonological skill was significantly lower in the Dys^{Phon} subgroup, who otherwise exhibited normal visual attention processing skills. On the contrary, the Dys^{Att} subgroup demonstrated poor visual attention abilities despite normal phonological skills. Interestingly, a close comparison of the two dyslexic subgroups further revealed that the Dys^{Att} subgroup associated significantly (r = -0.817, p = .012) with normal word reading (i.e. WIAT-II reading) compared to the Dys^{Phon} subgroup (r = -0.728, p = .041). Considering the effects from both dyslexic subgroups, this goes to show that a problem with visual attention had a slightly greater impact on normal word reading than a phonological problem. However, both dyslexic subgroups showed a higher correlation in nonword reading (i.e. TOWRE-PDE) over normal word reading, with Dys^{Att} subgroup (r = -0.964, p < .001) again demonstrating to be the most potent compared to the Dys^{Phon} subgroup (r = -0.836, p < .001). This suggests that nonword reading impairment in dyslexia can result from either a visual attention or phonological deficit (e.g. Bosse et al., 2007), and not necessarily based on a combination of two modalities. The former refers to a possible reduction in visual attention span potent enough to hamper the entire letter sequence of words required to be processed within a solitary step (e.g. Valdois et al., 2004), while the latter refers to an impaired knowledge of grapheme-to-phoneme correspondences (e.g. Ramus & Szenkovits, 2008).

In order to explore more in-depth the associations between cognitive disorders and their behavioral manifestations, it is important to look at the two dyslexic subgroups to explore the extent to which cognitive impairments differently modulated literacy performance. With regards to the Dys^{Phon} subgroup, enhanced crowding turned out to be a slightly stronger predictor of WIAT-II word reading performance (r = -0.728, p = .018) than TOWRE-SWE (r = -0.714, p = .027). This finding is to some extent in line with that previously demonstrated by Callens et al (2013), just that the latter reported a stronger correlation between crowding and both word along with nonword reading. Under these conditions, crowding in dyslexia is generally attributed to poor letter position encoding deficits (e.g. Collis, Kohnen, & Kinoshita, 2012). That is, greater a word extends into the visual periphery (i.e. long words) from the central foveal region, this leads to impaired letter-string identification due to the influence of crowding (Pelli et al., 2007). One potential manner in which dyslexics cope with crowding would be to analyse a given word broken down into its constituent short syllable segments. Nevertheless, such dyslexic individuals show significantly greater impairment on timed, compared to untimed reading measures (e.g. Waber et al., 2004; Wolf et al., 2000). Based on the word formats for both TOWRE-SWE (see **Appendix 4**) and PDE (see **Appendix 5**) measures, the former in particular had a ratio of 38 (≥ two syllabus) is to 15 (≥ three syllabus) words compared to the latter (16 ≥ two : 6 ≥ three syllabus), which suggest the difficulties which AwDys face with timed word reading, especially with a greater number of syllable words. The finding based on the association between nonword reading and set-size deficit is consistent with previous research, identifying this to be a result of an impaired phonological decoding process brought about by intervening perceptual noise (e.g. Perry et al., 2007).

The key however is that a majority of studies which reported evidence of attention deficits were totally independent from phonological deficits (e.g. Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2012). This provides the licence to freely explore the visual attention domain specific deficits in relation to the observed literacy within the Dys^{Att} subgroup. From the correlation matrix (**Table 9**), it is evident that a larger proportion of effects were explained by deficits related to visual attention, compared to the phonological modality.

First, crowding was significantly associated with TOWRE-SWE measure (*r* = 0.849, p = .008) a finding which was common to the Dys^{Phon} subgroup. One explanation for this crowding problem in dyslexia is the impaired ability to focus visual attention on each successive letter within a word whilst simultaneously excluding the distractions caused by adjacent letters within the same word (Martelli et al., 2009; Schneps et al., 2013; Spinelli et al., 2002). By increasing the spacing between six letter words, dyslexic individuals demonstrated improved fluency of text reading (Perea et al., 2012). Similarly Zorzi & colleagues (2012) reported improved reading speeds and accuracy in dyslexic individuals upon increasing inter-letter spacing. In the same vein, the findings from studies 2 and 3 are consistent with an attentional explanation of the crowding effect experienced by AwDys, a result in line with diffusely allocated spatial attentional resources (e.g. Facoetti et al., 2001). Second, the finding of a strong association between set-size with that of WIAT-II word and nonword reading in the Dys^{Att} subgroup, further demonstrates the inhibitory aspects of attention crucial for perceptual noise exclusion, a function known to be impaired in dyslexic individuals (e.g. Facoetti et al., 2010; Roach & Hogben, 2007; Ruffino et al., 2010, 2014; Sperling et al., 2005). Furthermore, the set-size effect from the current batch of studies is consistent with the idea of a poor filtering function of visual attention, i.e. an impaired ability to focus attention during the processing of reading letters in a serial fashion, which results in poor phonological decoding ability due to the prevailing perceptual noise (Roach & Hogben, 2008). To that end, studies assessing attention shifting in dyslexia have related the role played by sluggish attention shifting to the capacity in which individuals with dyslexia are able to exclude external perceptual noise (e.g. Geiger et al., 2008; Sperling et al., 2005).

Interestingly, the strong correlation between influences of left visual field with nonword reading within the Dys^{Att} subgroup, despite being consistent with some of the previous studies in CwDys using non-linguistic stimuli (e.g. Facoetti et al., 2001, 2006), it turns out that it wasn’t in proportion to Judge et al (2007, 2013), with the latter reporting an absence of visual field asymmetry using letters in AwDys. Facoetti et al (2006) suggested that a selective nonword reading impairment was a result of poor attention focusing which influence the process of sublexical grapheme parsing. The authors further implied such visual attention deficits were evident only within specific dyslexic subtypes consisting of a single nonword deficit, rather than a broad array of phonological deficits. The findings based on the present thesis (**Chapter 5**) complements this point made by the authors, since participants within the Dys^{Att} subgroup having difficulties with nonword reading (i.e. TOWRE-PDE) under conditions specific to the left visual field asymmetry effect did not show any form of difficulty with the other reading measures (i.e. WIAT-II and/or TOWRE-

SWE). However, the absence of a similar pattern of effect within the Dys^{Phon} subgroup seems quite surprising. According to the dual-route model of reading (Perry et al., 2007), both phonological and visuospatial attention mechanisms together drive the process of grapheme parsing from the left spanning across the right visual field. In this regard, any nonword reading difficulty resulting from a visual attention processing deficit in AwDys is therefore indicative of a problem with the sublexical route which employs both phonological and attentional processing. One possible reason for the absence of such an effect could be down to the fewer number of participants (5) within the Dys^{Phon} subgroup. Nevertheless, the visual attentional tasks within the Dys^{Att} subgroup accounted to 83.5% of unique variance in phonological decoding, representing an excellent predictor of nonword reading. Taken together, this goes to show that a single attentional disorder further accounts for mixed reading profiles in AwDys much more significant compared to a phonological disorder.

Chapter 8:

Concluding Remarks

8.1 Conclusions

This thesis presents findings from one analytical and three behavioural studies investigating attention modulation in dyslexia using a tilted target detection and discrimination. The first study (**Chapter 2**) investigated attention deficits involving visual crowding based on stimulus displays with constant (set-size 8) noise (from seven neighbouring distractors surrounding a single tilted target) further modulated by valid visual cues. Findings showed that AwDys on visual search tasks was significantly affected by visual crowding. Compared to controls, AwDys showed a greater dependence on pre-cues to make accurate orientation discrimination judgements. In particular, AwDys were only able to make use of the pre-cues (unlike post-cues) to eliminate the effects of visual crowding. The second study (**Chapter 3**) employing an identical visual search paradigm, but this time including a set-size manipulation (noise variant) indicated that AwDys in high external noise having poor overall performance in visual search significantly affected by both visual crowding and set-size. Although AwDys made use of the pre-cues to eliminate the effects of visual crowding, they were less able to make use of both the pre and post-cues to eliminate set-size effects. Task difficulty also had a significant impact especially in conditions of higher noise. Although these findings were broadly concordant with that of Roach & Hogben (2004) signifying a noise exclusion deficit at a late decisional stage, study 2 also showed the same with AwDys using post-cues less effectively. The extent to which pre-cue dependence was correlated with the influence of crowding and set-size reflected closely on the observed literacy measures. On the basis of the evidence gathered initially, a broader and weaker spatial window of attention (i.e. attention spotlight) explained the difficulties AwDys come across when a crowded visual display was presented to them (Facoetti et al., 2000; Romani et al., 2011). The extent to which this spotlight orientated entirely depended on how well AwDys were able to make use of the pre-cues. It was thought that, should this spotlight turn out to be weaker and broader compared to that of control participants, then distractors present at the periphery may not be fully excluded potentially causing visual confusion (e.g. Stein & Walsh, 1997).

The third study (**Chapter 4**) employed a similar tilt discrimination task but this time round, the participants were not required to perform any visual search (non-search task as opposed to a tilt discrimination search task in our first study), in this way we were able to infer whether the observed crowding and set-size difficulty in study 2 was down to (i) internal decision noise (for which case we reduced the spatial uncertainty within the paradigm) and/or down to poor detection of the target (for which case we ensured the targets were presented in one of two locations), the latter which provided an added flexibility to assess spatial attention distribution. Participants were selected regardless of inattentive or hyperactive symptoms which were then measured and used as a covariate in the analysis. The results obtained from this study provided a firm grounding which extended from the previous two studies where, AwDys even under the influence of simple visual stimuli: (i) were affected by close spacing of distractors (crowding), (ii) were severely hampered by increasing distractor noise (set-size effect indicative of a noise exclusion deficit), and (iii) the effects of crowding along with set-size ended up being closely associated with measures of word reading, non-word reading and spelling. Findings also illustrated (iv) an asymmetrical distribution of visuo-spatial attention in AwDys. All three findings were consistent from those previously carried out concerning crowding (Spinelli et al., 2002), set-size (Roach & Hogben, 2007) and attention asymmetry (Facoetti et al., 2001). It was also clear that location uncertainty which presumably confounded decision and discrimination (in studies 1 and 2) provided results that are consistent with study 3 which isolated perceptual processing by eliminating location uncertainty. Thus, conditions with location uncertainty reflect more than just decision biases, at least in the absence of cues which provided spatial information about the target location. Taken together, these findings reflect deficits in visual-spatial attention in dyslexia (at least within the adult population) explained by noise exclusion deficits under the influence of simple visual stimuli. Although a forth behavioural accompanied by an fMRI study (**Chapter 6**) was meant to investigate potential attentional focusing deficits in AwDys, unfortunately the study came to an abrupt halt due to unexpected circumstances.

Interestingly, the analytic study (**Chapter 5**) demonstrated the presence of subtypes, even in a study where outward phenotypic difficulties in adult dyslexics were quite evident. That is, although dyslexic participants did demonstrate a significant effect of phonology related deficits (e.g. nonword reading), the way poor performance on literacy interacted with attentional deficits was quite surprising. Despite an absence of a double deficit, the present sample of adult dyslexics conformed to a higher percentage in the attentional subtype compared to the phonology subtype.

Taken together, these findings provide sufficient evidence to suggest that noise exclusion difficulties was more than capable of explaining the reported visual attention difficulties in AwDys, given such difficulties were associated with literacy. Moreover, these effects cannot be accounted for by ADHD or phonological difficulties. As per the latter, the task employed in the present study was purely visual having identical cognitive requirements in all conditions. A weaker and asymmetric attention observed in AwDys can therefore further explain the noise exclusion and visual crowding deficits. The crowding effect in AwDys suggests a diffused mode of visual attention and/or diminished visual attention span. The noise exclusion deficit in AwDys demonstrated different degrees of attentional modulation depending on task demands, either influenced by the contrasting noise (number of distractors) or by the complexity of processing (task difficulty). The interaction between task difficulty and some of the main effects emphasizes the need for stringent controlling of sensory factors. Despite such positive outcomes in the present study, the quest in search for one unified theory which completely explains all these findings continues, but the findings from the current batch of studies is no exception.

8.2 Research Implications

Clinical Assessments and Sub-grouping

Findings from the current set of behavioral studies indicate that both crowding and set-size effects could be associated with a broader and weaker spatial window (i.e. attention spotlight). A very good explanation for this in the context of crowding is visual span. Crowding, as many studies have shown in the past is very much inclined to occur in reading at both a letter and word level where the visual span limits reading speed. In adult fluent readers, the visual span equals the number of characters that are not crowded, proportional to the reading rate (Pelli & Tillman, 2008) unlike in AwDys. For instance, a finding by Dubois & Valdois (2010) in a sample of CwDys showed a strong correlation between small visual spans and slow reading rate and in nearly half of them (4 of 10) reading slowness was accounted for by the visual span shrinkage. This goes to show that when the search array is crowded, a weaker and broad attentional spotlight cannot isolate the correct set of features between target and distractor. Alternatively, such a deficit could affect reading directly, where dyslexia sufferers may find it difficult in discriminating individual letter (in a word) and words (in a sentence).

However, in terms of distractor exclusion, the deficit could be part of a wider difficulty in the filtering (excluding) of external noise (Sperling et al., 2005). In a study conducted by Sperling, Lu, Manis, & Seidenberg (2006), the authors highlighted that the presence of perceptual distractors (i.e., noise) in a motion detection task decreases dyslexics' performance as compared to when noise was removed from an experimental setting. Moreover, experimental evidence has previously shown that dyslexics are impaired in detection of a brief visual signal rapidly followed by noise (Facoetti et al., 2008) and that they are disturbed by lateral masking (Spinelli et al., 2002; Geiger et al., 2008; Martelli et al., 2009). The spatial processing windows, in which noise interferes with the signal, appear to be broader in CwDys compared to normally reading children (Geiger et al., 2008). Thus, the broader spatial window in dyslexia could be a plausible effect of attentional engagement deficit specifically shown in people with dyslexia which could therefore influence the filter-out mechanism of irrelevant lateral letters during graphemic parsing (Facoetti, et al., 2006; Facoetti, et al., 2010).

These present findings have rather important implications from a clinical outlook. Even though one is capable of assigning a given individual as being dyslexic based on reading profiles (which in absolute fact is deemed necessary when it comes to monitoring the progress of reading skills), the findings from this thesis signifies the unreliability of such language measures alone especially when identifying cognitive disorders closely linked with reading difficulties. Sometimes it becomes easy to spot outward phenotypic cues pertaining to an underlying cognitive deficit based on reading and spelling performance. However, based on the findings from this study at least, it would be a positive move by a respective clinician to include supplementary examinations specific to a given battery of associated cognitive disorders. Although, measuring phonological performance is crucial, the present batch of findings indicates that poor nonword reading is by no means satisfactory to infer the existence of a fundamental phonological disorder. Measures specific to noise filtering, visual attention span, and crowding are some of the investigations which must be encouraged (at least within the adult population), given such attentional abilities are also influential when learning to read and throughout development as a whole. This practice is quite crucial not only for the purposes of identification of a deficit, but also to carry out remediation programs to help dyslexic individuals improve their reading performance.

8.3 Research Limitations

In the current study, we set out to investigate the extent to which both controls and AwDys search performance of an orientation detection task varied with a variety of factors namely cueing, set size, task difficulty and spacing, all of which have been closely involved with dyslexia. In previous studies, the influence of each of these factors has been studied independently thus producing inconsistent results. This inconsistency could have been due to the sensitivity of the task imposed as a result of limitations within the paradigm tested or it could be the extent of severity in a given pool of AwDys. In the current study, in spite of calibrating the overall performance across the conditions and presenting the search arrays for significantly longer to the AwDys, a significant main effect of group on accuracy was evident. Despite that, performance of AwDys was far lower than performance of controls even in the presence of a single stimulus when left un-cued. It was for this very reason that analyses were first split by group; so that relative (rather than absolute) performance across conditions could be compared i.e. attention modulation. Furthermore, the modulatory effects of both cueing and crowding cannot be accounted for by phonological difficulties since the task was a purely visual based and has identical cognitive requirements in both conditions as variations in stimuli occurred with cueing and/ or spacing.

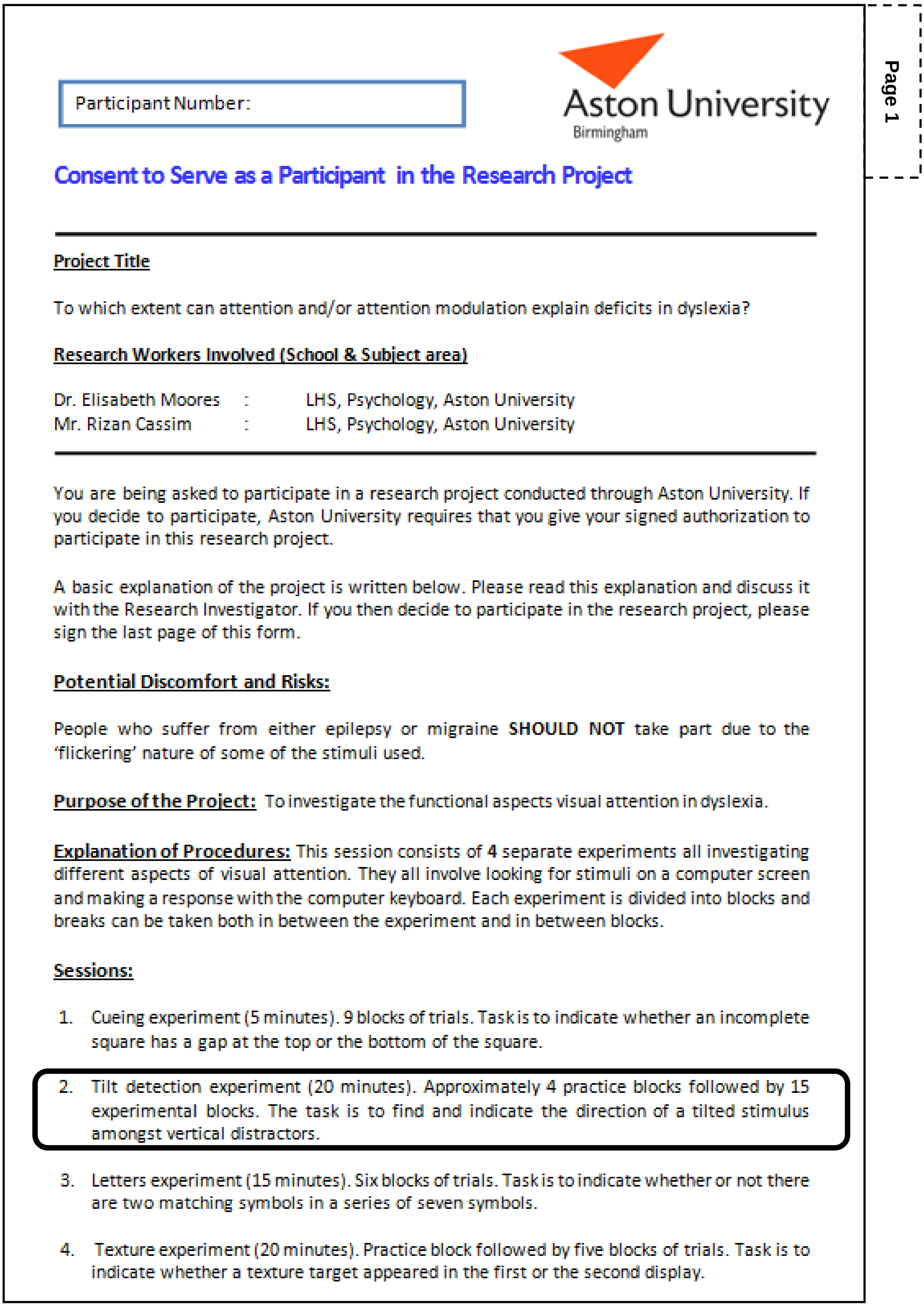
8.4 Future Work

Obviously an important issue for future research is to gain a deeper insight about the role of such noise exclusion deficits found in dyslexia. Of particular interest is whether AwDys have a problem in narrowing down attention. Firstly, given that AwDys were able to move their attention (for instance, using pre-cues in our previous study), it could be that they are not zooming in/narrowing down their attention efficiently as they should. This may imply why AwDys were unable to exclude irrelevant information which they were not expected to focus (current study). Secondly, despite attempts to equate overall performance in both these studies, a significant main effect of group was observed for a set-size effect, the pattern of performance may possibly be reflected due to greater overall difficulty with the perceptual task itself, an important sensory factor that needs controlling for in our future studies. One way to address this is in the use of functional magnetic resonance imaging (fMRI) technique in the context of attention directed stimulus specific activation. That is, we are able to measure the precise response to distracting (noisy) stimuli without affecting the participants’ ability to deploy attention. This way, we’d be in a better position to show any prevailing difficulty in dyslexic individuals when it comes to excluding peripheral distractors at a neural level rather than a response level, a fact that many studies have capitalized on for decades. While studies on attention control are only just beginning to parse the components of the attention control system, as far as we are concerned, our intended future study would be the first of its kind to investigate attention modulation in developmental dyslexia with reference to the poor attentional filtering.

APPENDICES

APPENDIX 1

Study 1 Consent Form



Page 1

Participant Number:

Aston University
Birmingham

Consent to Serve as a Participant in the Research Project

Project Title

To which extent can attention and/or attention modulation explain deficits in dyslexia?

Research Workers Involved (School & Subject area)

Dr. Elisabeth Moores : LHS, Psychology, Aston University
Mr. Rizan Cassim : LHS, Psychology, Aston University

You are being asked to participate in a research project conducted through Aston University. If you decide to participate, Aston University requires that you give your signed authorization to participate in this research project.

A basic explanation of the project is written below. Please read this explanation and discuss it with the Research Investigator. If you then decide to participate in the research project, please sign the last page of this form.

Potential Discomfort and Risks:

People who suffer from either epilepsy or migraine **SHOULD NOT** take part due to the 'flickering' nature of some of the stimuli used.

Purpose of the Project: To investigate the functional aspects visual attention in dyslexia.

Explanation of Procedures: This session consists of **4** separate experiments all investigating different aspects of visual attention. They all involve looking for stimuli on a computer screen and making a response with the computer keyboard. Each experiment is divided into blocks and breaks can be taken both in between the experiment and in between blocks.

Sessions:

1. Cueing experiment (5 minutes). 9 blocks of trials. Task is to indicate whether an incomplete square has a gap at the top or the bottom of the square.
2. Tilt detection experiment (20 minutes). Approximately 4 practice blocks followed by 15 experimental blocks. The task is to find and indicate the direction of a tilted stimulus amongst vertical distractors.
3. Letters experiment (15 minutes). Six blocks of trials. Task is to indicate whether or not there are two matching symbols in a series of seven symbols.
4. Texture experiment (20 minutes). Practice block followed by five blocks of trials. Task is to indicate whether a texture target appeared in the first or the second display.

Estimated time: The estimated time for each experiment (without breaks) is indicated above. However, we expect breaks to be taken so that the total testing time could be up to 90 minutes. You can withdraw from testing at any time and be paid for the proportion of testing that you have completed.

Payment for participation: Participants will be awarded **£15** on completion of the allocated tests.

Participation: Your participation in this research project is completely voluntary. Your decision not to participate in this project will not result in any penalty. You may withdraw from the above project at any time.

Confidentiality: All personal information provided along with the responses of this experiment will remain confidential. No information that identifies you as the participant will be publically available; rather all data will be pooled and published in aggregate form only. The participant's data on the computer will be identified by a unique number rather than the name for added confidentiality.

Volunteer's Statement:

By signing this consent form, you agree to participate in this research project. The purpose, procedures to be used, and the potential risks and benefits of your participation have been explained to you in detail. You can refuse to participate or withdraw from this research project at any time without penalty. Refusal to participate in this study or withdrawal from this study will have no effect on any services you may otherwise be entitled to and from Aston University. You will be given a copy of this consent form.

Participant Signature ______________________ Date ______________________

Signature of Research Worker ______________________ Date ______________________

If you have any further questions or want to inquire more about this project in the future, please do not hesitate to contact me via cassimrm@aston.ac.uk.

APPENDIX 2

Words used for the WIAT-II Spelling test

Two
Under
Right
Jumped
Charge
Knew
Careless
Guess
Riding
Rough
Climbed
Couldn’t
Whistle
Owe
Design
Easier
Strength
Doubt
Ceiling
Absence
Accept
Patients
Beginning
Excitement
Subsidise
Edition
They’re
Principal
Received
Assistants
Prestigious
Sovereign
Pharmaceutical
Accommodate
Conscientious

APPENDIX 3

Words used for the WIAT-II Word Reading test

rhythm	courage	determine
ajar	apology	**AGES 21 & OVER**
ruin	dozing	useless
ideally	deputy	cutlery
phonograph	poise	unique
pathetic	cleanse	chord
acquire	scholar	treacherous
veterinary	ridicule	vicinity
negotiate	catastrophe	infamous
topography	naive	subtle
bureau	plethora	reminisce
conscience	indefatigable	malign
indigenous	euphemism	milieu
antithesis	ethereal	hierarchical

APPENDIX 4

Words used for the TOWRE (SWE)

is
up
cat
red
me
to
no
we
he
the
and
yes
of
him
as
book
was
help
then
time
wood
let
men
baby
new
stop
work
jump
part
fast
fine
milk
back
lost
find
paper
open
kind
able
shoes
money
great
father
river
space
short
left
people
almost
waves
child
strong
crowd
better
inside
plane
pretty
famous
children
without
finally
strange
budget
repress
contain
justice
morning
resolve
describe
garment
business
qualify
potent
collapse
elements
pioneer
remember
dangerous
uniform
necessary
problems
absentee
advertise
pleasant
property
distress
information
recession
understand
emphasis
confident
intuition
boisterous
plausible
courageous
alienate
extinguish
prairie
limousine
valentine
detective
recently
instruction
transient

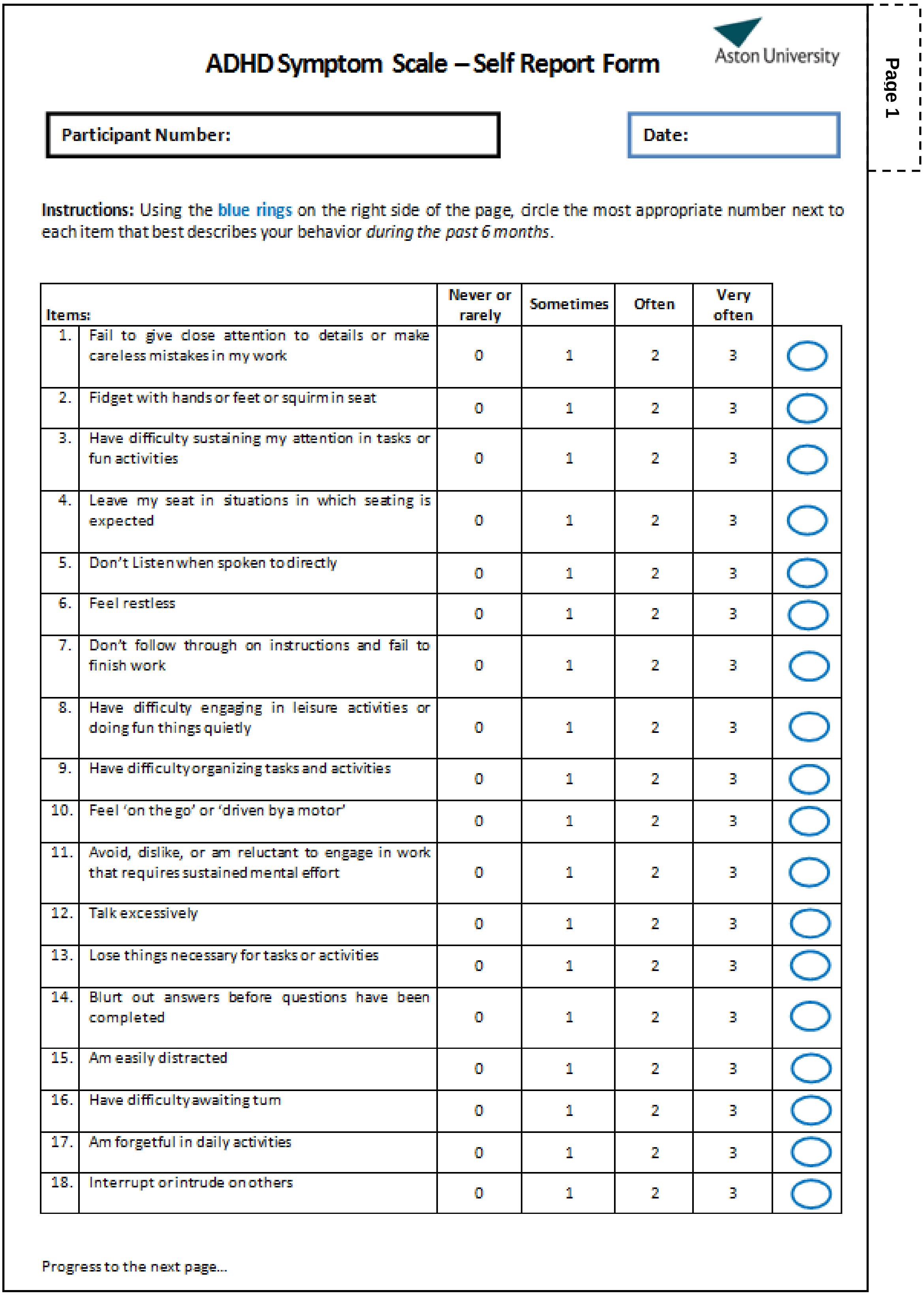
APPENDIX 5

Words used for the TOWRE (PDE)

mo
ik
pu
bi
ib
ku
eb
pog
dat
mip
ral
nas
mib
faw
shum
bice
nade
teap
derl
marl
berk
mest
stree
weaf
barch
glack
prot
runk
loast
mact
blork
phet
wogger
klup
skad
keast
churt
glamp
prait
flact
throbe
creft
flimp
girtus
strale
debmer
happon
framble
progus
supken
jeltlic
tegwop
slinperk
plinders
thundelp
bramtich
chimdruff
darlankert
stremfick
morlingdon
revignuf
obsorfelm
pitocrant

APPENDIX 6

Self reporting ADHD questionnaire



Page 1

Aston University

ADHD Symptom Scale – Self Report Form

Participant Number:

Date:

Instructions: Using the blue rings on the right side of the page, circle the most appropriate number next to each item that best describes your behavior *during the past 6 months*.

Items:		Never or rarely	Sometimes	Often	Very often	
1.	Fail to give close attention to details or make careless mistakes in my work	0	1	2	3	○
2.	Fidget with hands or feet or squirm in seat	0	1	2	3	○
3.	Have difficulty sustaining my attention in tasks or fun activities	0	1	2	3	○
4.	Leave my seat in situations in which seating is expected	0	1	2	3	○
5.	Don't Listen when spoken to directly	0	1	2	3	○
6.	Feel restless	0	1	2	3	○
7.	Don't follow through on instructions and fail to finish work	0	1	2	3	○
8.	Have difficulty engaging in leisure activities or doing fun things quietly	0	1	2	3	○
9.	Have difficulty organizing tasks and activities	0	1	2	3	○
10.	Feel 'on the go' or 'driven by a motor'	0	1	2	3	○
11.	Avoid, dislike, or am reluctant to engage in work that requires sustained mental effort	0	1	2	3	○
12.	Talk excessively	0	1	2	3	○
13.	Lose things necessary for tasks or activities	0	1	2	3	○
14.	Blurt out answers before questions have been completed	0	1	2	3	○
15.	Am easily distracted	0	1	2	3	○
16.	Have difficulty awaiting turn	0	1	2	3	○
17.	Am forgetful in daily activities	0	1	2	3	○
18.	Interrupt or intrude on others	0	1	2	3	○

Progress to the next page...

How old were you when these problems with attention, impulsiveness, or hyperactivity first began to occur?

☐ Years old

To what extent do the problems you may have just indicated (in page 1) interfere with your ability to function in each of these areas of life activities?

Page 2

Areas:	Never or rarely	Sometimes	Often	Very often	
In my home life with my immediate family	0	1	2	3	○
In my work or occupation	0	1	2	3	○
In my social interactions with others	0	1	2	3	○
In my activities or dealings in the community	0	1	2	3	○
In any educational activities	0	1	2	3	○
In my dating or marital relationship	0	1	2	3	○
In my management of my money	0	1	2	3	○
In my driving of a motor vehicle	0	1	2	3	○
In my leisure or recreational activities	0	1	2	3	○
In my management of my daily responsibilities	0	1	2	3	○

Instructions: Again, using the red rings on the right side of the page, circle the most appropriate number next to each item that best describes your behavior *during the past 6 months*.

Areas:		Never or rarely	Sometimes	Often	Very often	
1.	Lose temper	0	1	2	3	○
2.	Argue	0	1	2	3	○
3.	Actively defy or refuse to comply with requests or rules	0	1	2	3	○
4.	Deliberately annoy people	0	1	2	3	○
5.	Blame others for my mistakes or misbehavior	0	1	2	3	○
6.	Am touchy or easily annoyed by others	0	1	2	3	○
7.	Am angry and resentful	0	1	2	3	○
8.	Am spiteful or vindictive	0	1	2	3	○

PS: Once fully completed, please email this form along with the others (as stated in the email) back to the chief investigator (cassimrm@aston.ac.uk).

This ADHD self report form was obtained from: Barkley, R.A. & Murphy, K.R. (2006). Attention-Deficit Hyperactivity Disorder: A Clinical Workbook (3rd ed.): *The Guilford Press*.

APPENDIX 7

Data Analysis for Study 3 using ANOVA

This results section focuses on analyzing participant responses from study 3 in line with: (i) the effects of crowding, (ii) attention distribution and distractor exclusion, and (iii) the relationship between literacy and crowding, set-size and VF effects. Participants were selected regardless of inattentive or hyperactive symptoms of ADHD for analysis. A summary table following each subsection compares the current ANOVA measures to that from the ANCOVA analysis conducted in **section 4.5.2**.

7.1 Visual crowding effects

7.1.1 Main Effects

A four-factor ANOVA based on the accuracy of orientation discriminability was carried out with group (controls, AwDys) as an independent factor, whilst the set-size two spacing (two-spread, two-crowded), task difficulty (easy, hard), and display side (left-VF, right-VF) served as repeated measures. Despite attempts to equate overall performance, a significant main effect of group ($F_{(1, 26)} = 52.91$, MSE = 0.009, $p < .001$, $\eta_p^2 = .67$) was evident, with higher group performance by controls compared to AwDys.

There were significant main effects of spacing ($F_{(1, 26)} = 11.19$, MSE = 0.009, $p = .003$, $\eta_p^2 = .30$), and task difficulty ($F_{(1, 26)} = 44.80$, MSE = 0.002, $p < 0.001$, $\eta_p^2 = .63$). However, the main effect of display side did not reach significance ($F_{(1, 26)} = 1.04$, MSE = 0.002, $p = .316$, $\eta_p^2 = .04$). The spacing by group interaction was significant ($F_{(1, 26)} = 9.69$, MSE = 0.009, $p = .004$, $\eta_p^2 = .27$) indicative of a reduced performance accuracy by AwDys group more than that by controls in crowded displays. There were also significant two-way interactions between task difficulty and group ($F_{(1, 26)} = 15.64$, MSE = 0.002, $p < 0.001$, $\eta_p^2 = .37$); spacing and task difficulty ($F_{(1, 26)} = 9.42$, MSE = 0.002, $p = .005$, $\eta_p^2 = 0.26$); followed by a three-way interaction between spacing, task difficulty and group ($F_{(1, 26)} = 5.64$, MSE = 0.002, $p = .025$, $\eta_p^2 = 0.17$). However, the four-way interaction between spacing, display side, task difficulty and group was not significant ($F_{(1, 26)} = 1.98$, MSE = 0.002, $p = .171$, $\eta_p^2 = .07$). No other main effects and interactions reached significance. As expected, these main effects suggests that a degraded discrimination performance was greatly influenced by the close spacing of distractors and the severity imposed by the difficulty of the task irrespective of which VF the stimuli were projected on to.

<u>7.1.2 Main Effects in terms of Group</u>

In order to probe both the effects of spacing and task difficulty in the main three-way interaction [i.e. spacing, task difficulty and group ($F_{(1,\ 26)} = 5.65$, MSE = 0.002, $p = .025$, $\eta_p^2 = 0.17$)], analysis were split with respect to each group. The descriptive statistics are summarised in **Figure A**.

There was a significant effect of spacing for AwDys ($F_{(1,\ 12)} = 21.44$, MSE = 0.008, $p < .001$, $\eta_p^2 = .64$) but not in controls ($F_{(1,\ 14)} = 0.02$, MSE = 0.010, $p = .872$, $\eta_p^2 = .02$). With an effect of task difficulty demonstrated by controls ($F_{(1,\ 14)} = 20.49$, MSE = 0.000, $p < 0.001$, $\eta_p^2 = .59$), AwDys too showed a significant effect of task difficulty ($F_{(1,\ 12)} = 27.32$, MSE = 0.004, $p < 0.001$, $\eta_p^2 = .69$) and an interaction between spacing and task difficulty ($F_{(1,\ 12)} = 7.15$, MSE = 0.004, $p = .020$, $\eta_p^2 = .373$). These findings illustrate a higher performance shown by the control group compared to AwDys. Although controls were not affected by crowded displays, AwDys were prone to reduced search performances in crowded displays. However, this was not the case for AwDys when displays were spread, where there was a lesser impact of task difficulty. In essence, this goes to show how significant a crowding effect caused by two distractors is on orientation discriminability in AwDys. The summary **Table V** on the next page summarises the identical findings as observed from both ANCOVA and ANOVA analysis.

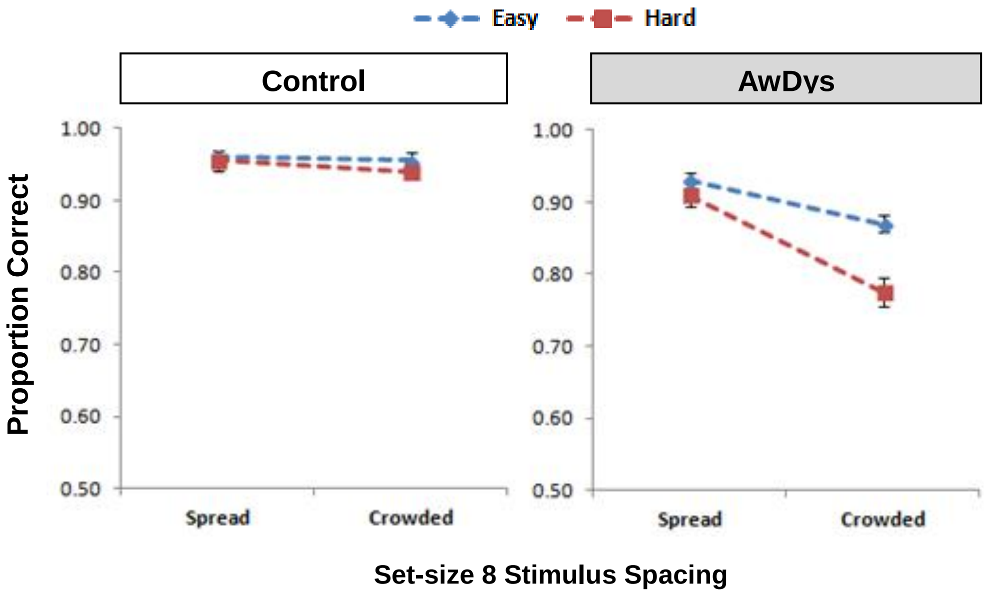
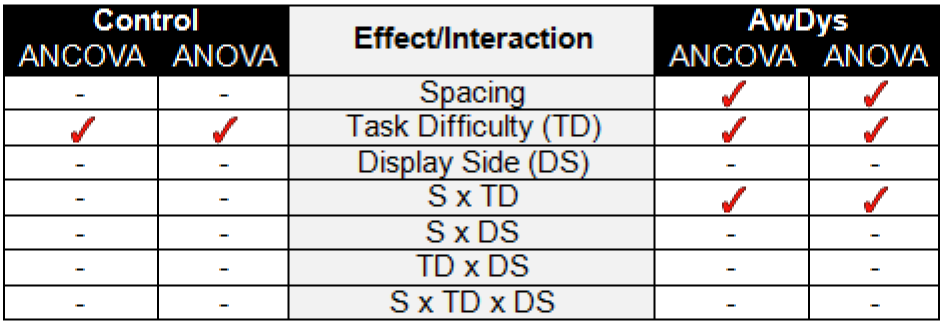


Figure A: Interaction plots indicating performance accuracy for both controls and AwDys plotted as a function of interstimulus spacing (crowded vs. spread) and task difficulty. Note that evidence for an interference based crowding effect in AwDys group as indicated by the steepness of the slope for crowded conditions. Error bars represent ±1 standard error of the mean percentage response accuracy.

Table V: Table summarising the effect of spacing along with its interactions with task difficulty and display side for both controls and AwDys. The use of ANOVA represents the participant cohort for this study where the data was analysed together with the influence of ADHD but without the participants who scored above the clinical level for ADHD. The use of ANCOVA represents the participant cohort for the same study, except this time the effects of ADHD had been removed from the group effect. "–" indicates a non-significant (p > .05) effect/interaction.



Control		Effect/Interaction	AwDys	
ANCOVA	ANOVA		ANCOVA	ANOVA
-	-	Spacing	✓	✓
✓	✓	Task Difficulty (TD)	✓	✓
-	-	Display Side (DS)	-	-
-	-	S x TD	✓	✓
-	-	S x DS	-	-
-	-	TD x DS	-	-
-	-	S x TD x DS	-	-

7.2. Attention Distribution and Distractor Exclusion

7.2.1 Main Effects

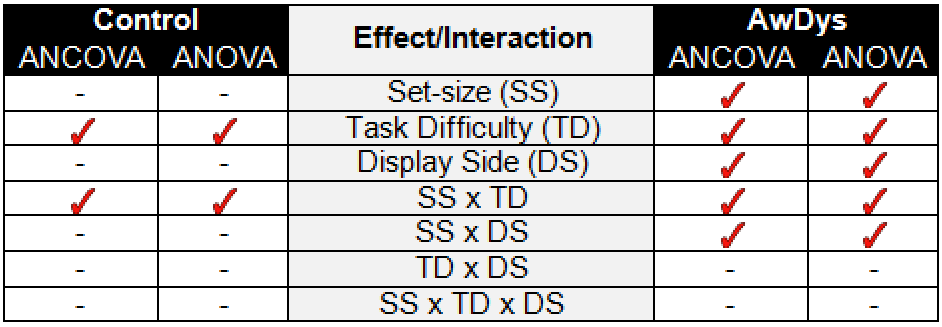
In order to examine the effect of set-size on orientation discriminability, the number of competing distractors was gradually increased whilst the spacing remained constant; this equated solely for distractor interferences. A four-factor ANOVA was carried out with group (controls, AwDys) as an independent factor, whilst set-size (zero, two-spread, four, eight), task difficulty (easy, hard) and display side (left-VF, right-VF) served as repeated measures. The analysis confirmed a main effect of group ($F_{(1, 26)} = 57.59$, MSE = 0.018, $p < .001$, $\eta_p^2 = 0.69$), and a multiple interaction effect, especially that of a four-way interaction between set-size, task difficulty, display side and group ($F_{(3, 78)} = 9.33$, MSE = 0.002, $p < .001$, $\eta_p^2 = .26$).

For sake of simplicity, analyses were carried out separately for each group using a three-factor ANOVA with set-size (zero, two-spread, four, eight), task difficulty (easy, hard) and display side (left-VF, right-VF) as repeated measures. The control group showed no main effect of set-size ($F_{(1, 14)} = 4.02$, MSE = 0.024, $p = .064$, $\eta_p^2 = 0.22$) although there was a significant main effect for task difficulty ($F_{(1, 14)} = 21.69$, MSE = 0.002, $p < .001$, $\eta_p^2 = .60$), and a two-way interaction between set-size and task difficulty ($F_{(3, 42)} = 8.13$, MSE =

0.001, $p < .001$, $\eta_p^2 = .36$). However, the main effect of display side ($F_{(1, 14)} = 0.06$, MSE = 0.001, p = .802, $\eta_p^2 = .00$), and interactions between set-size and display side ($F_{(3, 42)} = 0.46$, MSE = 0.001, p = .707, $\eta_p^2 = .03$); task difficulty and display side ($F_{(1, 14)} = 0.13$, MSE = 0.002, p = .721, $\eta_p^2 = .01$); and set-size, task difficulty and display side ($F_{(3, 42)} = 0.24$, MSE = 0.001, p = .862, $\eta_p^2 = .17$) were not statistically significant. These findings are consistent with the expectation of higher performance accuracy in displays irrespective of the number of distractors that are present on a given visual field.

In contrast, the AwDys group showed significant effects of set-size ($F_{(3, 36)} = 37.25$, MSE = 0.017, $p < 0.001$, $\eta_p^2 = .75$); task difficulty ($F_{(1, 12)} = 45.30$, MSE = 0.005, $p < .001$, $\eta_p^2 = .79$) and display side ($F_{(1, 12)} = 68.66$, MSE = 0.003, $p < .001$, $\eta_p^2 = .85$). In addition, there were significant interactions between set-size and task difficulty ($F_{(3, 36)} = 14.41$, MSE = 0.003, $p < .001$, $\eta_p^2 = .54$), and set-size and display side ($F_{(3, 36)} = 38.30$, MSE = 0.003, $p < .001$, $\eta_p^2 = .76$), unlike for task difficulty and display side ($F_{(1, 12)} = 4.82$, MSE = 0.001, p = .626, $\eta_p^2 = .01$), and the three-way interaction between set-size, task difficulty and display side ($F_{(3, 36)} = 2.56$, MSE = 0.001, p = .538, $\eta_p^2 = .01$). This poor performance by AwDys was apparent only when (i) the discrimination remained difficult for a stimulus appearing on a given display side, and (ii) whilst subjected towards varying numbers of distractors. The summary **Table W** summarises the identical findings as observed from both ANCOVA and ANOVA analysis.

Table W: Table summarising the effect of set-size along with its interactions with task difficulty and display side for both controls and AwDys. The use of ANOVA represents the participant cohort for this study where the data was analysed together with the influence of ADHD but without the participants who scored above the clinical level for ADHD. The use of ANCOVA represents the participant cohort for the same study, except this time the effects of ADHD had been removed from the group effect. "–" indicates a non-significant (p > .05) effect/interaction.



Control		Effect/Interaction	AwDys	
ANCOVA	ANOVA		ANCOVA	ANOVA
-	-	Set-size (SS)	✓	✓
✓	✓	Task Difficulty (TD)	✓	✓
-	-	Display Side (DS)	✓	✓
✓	✓	SS x TD	✓	✓
-	-	SS x DS	✓	✓
-	-	TD x DS	-	-
-	-	SS x TD x DS	-	-

7.2.2 Influence of Task Difficulty on Distractor Exclusion

To determine whether groups differed on their ability to exclude distractors given the influence of task difficulty, the four-way interaction (i.e. set-size, task difficulty, display side and group) was further examined by splitting the analyses by display side and group for performance differences between task difficulties. Two separate, two-factor ANOVAs were conducted in order to investigate whether the effects of set-size (zero, two-spread, four, eight) differed for each group (control, AwDys) as a function of task difficulty (easy, hard). The corresponding interaction plots are as shown in **Figure B**.

AwDys showed a significant main effect of set-size ($F_{(3,\ 36)} = 16.28$, MSE = 0.012, $p < .001$, $\eta_p^2 = .48$); display side ($F_{(1,\ 12)} = 24.19$, MSE = 0.002, $p < .001$, $\eta_p^2 = .58$); and a two-

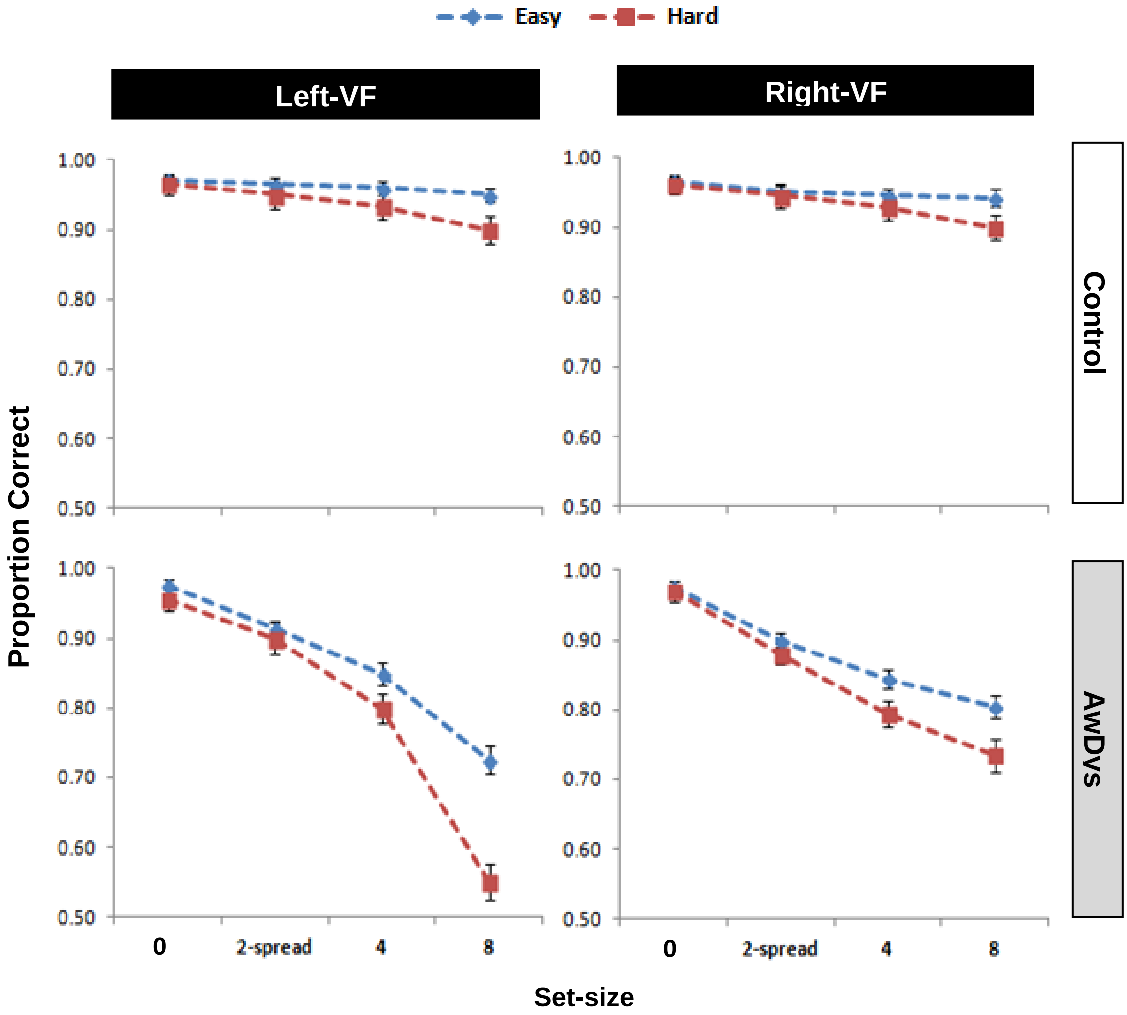


Figure B: Descriptive statistics showing performance accuracy for both controls (top horizontal panel) and AwDys (bottom horizontal panel) for the stimulus display side conditions (left vs. right-VF) plotted as a function of set-size and task difficulty. Error bars represent ±1 standard error of the mean percentage response accuracy.

way interaction between set-size and display side ($F_{(3, 36)} = 5.45$, MSE = 0.002, $p = .002$, $\eta_p^2 = .24$) whilst the task discriminations were easy. Similarly, even when the tasks were hard, AwDys demonstrated a significant main effect of set-size ($F_{(3, 36)} = 70.32$, MSE = 0.009, $p < .001$, $\eta_p^2 = .80$); display side ($F_{(1, 12)} = 49.37$, MSE = 0.004, $p < .001$, $\eta_p^2 = .79$); and set-size by display side interaction ($F_{(3, 36)} = 50.99$, MSE = 0.004, $p < .001$, $\eta_p^2 = .75$). In contrast, none of the effects or interactions demonstrated by the control group was significant irrespective of task difficulty (Fs < 1).

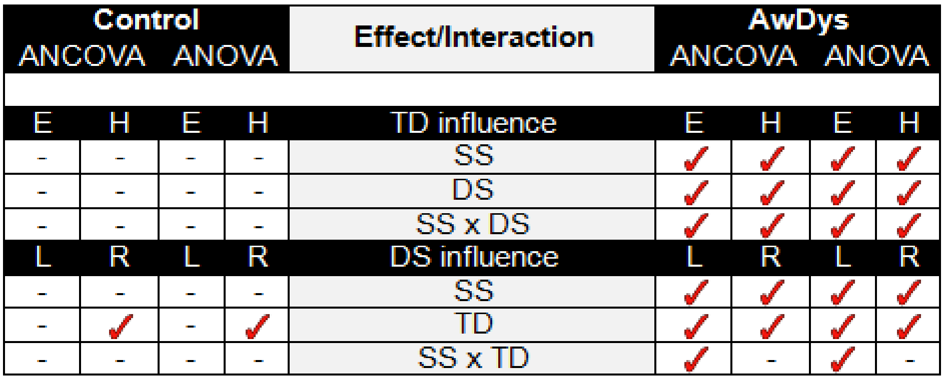
7.2.3 Influence of Visual Field on Distractor Exclusion

To determine whether groups differed on their ability to exclude distractors given the influence of VF-effects, the four-way interaction previously (i.e. set-size, task difficulty, display side and group) was further examined by splitting the analyses by task difficulty and group for performance differences between display sides. Two separate, two-factor ANOVAs were conducted in order to investigate whether the effects of set-size (zero, two-spread, four, eight) differed for each group (control, AwDys) as a function of display side (left-VF, right-VF). The corresponding interaction plots are as shown in **Figure B**.

For stimuli appearing on the left-VF, a significant main effect of set-size was evident in AwDys ($F_{(3, 36)} = 64.60$, MSE = 0.010, $p < .001$, $\eta_p^2 = .84$) but not in controls ($F_{(3, 42)} = 3.92$, MSE = 0.011, $p = .067$, $\eta^2_p = .11$). Both the effects of task difficulty ($F_{(1, 14)} = 6.09$, MSE = 0.008, $p = .095$, $\eta_p^2 = .07$), and the set-size by task difficulty interaction ($F_{(3, 42)} = 2.09$, MSE = 0.001, $p = .117$, $\eta_p^2 = .02$) demonstrated by controls did not reach significance. However, the AwDys showed significant effects of task difficulty ($F_{(1, 12)} = 40.83$, MSE = 0.005, $p < .001$, $\eta_p^2 = .77$), and a set-size by task difficulty interaction ($F_{(3, 36)} = 17.80$, MSE = 0.004, $p < .001$, $\eta_p^2 = .59$).

For stimuli appearing on the right-VF, a significant main effect of set-size was evident in the AwDys ($F_{(3, 36)} = 12.18$, MSE = 0.010, $p < .001$, $\eta_p^2 = .50$) unlike that in controls ($F_{(1, 42)} = 3.60$, MSE = 0.015, $p = .079$, $\eta_p^2 = .20$). Although the controls showed a significant main effect of task difficulty ($F_{(1, 14)} = 23.84$, MSE = 0.001, $p < .001$, $\eta_p^2 = .63$) similar to AwDys ($F_{(1, 12)} = 18.98$, MSE = 0.003, $p < .001$, $\eta_p^2 = .61$), the set-size by task difficulty interaction narrowly missed significance for controls ($F_{(3, 42)} = 3.03$, MSE = 0.003, $p = .058$, $\eta_p^2 = .17$) whilst it was not significant for AwDys ($F_{(3, 36)} = 1.32$, MSE = 0.002, $p = .280$, $\eta_p^2 = .10$). With all the above main effects and interactions taken as a whole and on the basis of the effect size/power (η_p^2) associated with each of these effects and interactions, it is evident that AwDys were more affected by increasing set-sizes on the left-VF (η_p^2 = 84%) unlike the right-VF (η_p^2 = 50%) especially when the discrimination was difficult. The effect of set-size was rather negligible for controls. The pattern of results was also consistent with the worse performance in AwDys being more pronounced at increasing set-sizes on the left-VF. The summary **Table X** summarises the identical findings as observed from both ANCOVA and ANOVA analysis.

Table X: Table summarising the effect of set-size along with its interactions with task difficulty and display side for both controls and AwDys. The use of ANOVA represents the participant cohort for study 3 where the data was analysed together with the influence of ADHD but without the participants who scored above the clinical level for ADHD. The use of ANCOVA represents the participant cohort for the same study, except this time the effects of ADHD had been removed from the group effect. "✓" indicates a significant effect/interaction (p < .001 or .05) whilst "–" indicates a non-significant (p > .05) effect/interaction. "L" refers to left-VF, "R" refers to right-VF, "E" refers to the easy, and "H" refers to the hard tasks respectively.



Control				**Effect/Interaction**	**AwDys**			
ANCOVA		ANOVA			ANCOVA		ANOVA	
E	H	E	H	TD influence	E	H	E	H
-	-	-	-	SS	✓	✓	✓	✓
-	-	-	-	DS	✓	✓	✓	✓
-	-	-	-	SS x DS	✓	✓	✓	✓
L	R	L	R	DS influence	L	R	L	R
-	-	-	-	SS	✓	✓	✓	✓
-	✓	-	✓	TD	✓	✓	✓	✓
-	-	-	-	SS x TD	✓	-	✓	-

7.3. Set-size and Distractor Exclusion

To determine the extent to which set-sizes influenced orientation discriminability, pair-wise comparisons for set-size were carried out separately for both groups (**Figure C left**).

For controls, apart from the only significant difference observed between set-size zero and set-size eight conditions [t(14) = 3.807, p = .002], no other differences were significant, i.e. set-size zero and two-spread [t(14) = 1.702, p = .111); set-size zero and four [t(14) = 1.164, p = .108]; set-size two-spread and four [t(14) = 1.643, p = .131]; set-size 2-spread and eight [t(14) = 1.444, p = .128], and set-size four and eight [t(14) = 1.597, p = .106]. This pattern of results demonstrated that the performance was generally similar across all the set-sizes.

Pair-wise comparisons in the AwDys group indicated significant differences between set-size zero and four [t(12) = -4.742, p < .001]; set-size zero and eight [t(12) = 25.285, p < .001]; set-size two-spread and four [t(12) = -3.338, p = .006]; set-size two-spread and eight [t(12) = 20.782, p < .001]; and set-size four and eight [t(12) = 8.871, p < .001]. The difference between set-size zero and two-spread conditions marginally missed statistical significance [t(12) = 2.390, p = .054]. Taken together, these findings suggest that, in AwDys, a severe impact as a result of increasing distractor numbers brought about the worse performance at the largest set-size (eight), whilst being able to perform better at the smallest set-size. The summary **table Y** summarises the identical findings as observed from both the ANCOVA and ANOVA analysis.

Table Y: Table summarising the effect of set-size along with its interactions with task difficulty and display side for both controls and AwDys. The use of ANOVA represents the participant cohort for this study where the data was analysed together with the influence of ADHD but without the participants who scored above the clinical level for ADHD. The use of ANCOVA represents the participant cohort for the same study, except this time the effects of ADHD had been removed from the group effect. "–" indicates a non-significant (p > .05) effect/interaction.

Control		Set-size Interactions	AwDys	
ANCOVA	ANOVA		ANCOVA	ANOVA
-	-	0 x 2-spread	-	-
-	-	0 x 4	✓	✓
-	-	2-spread x 4	✓	✓
-	-	2-spread x 8	✓	✓
-	-	4 x 8	✓	✓
✓	✓	0 x 8	✓	✓

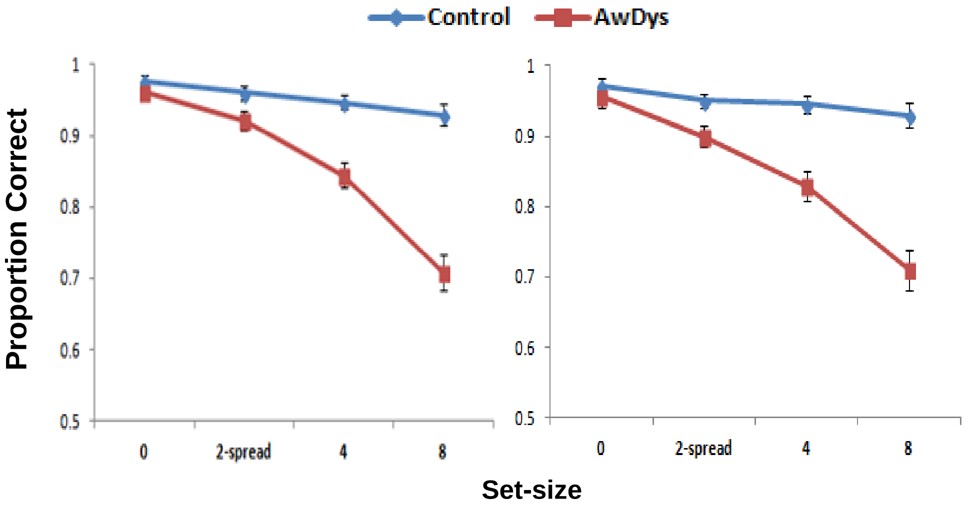


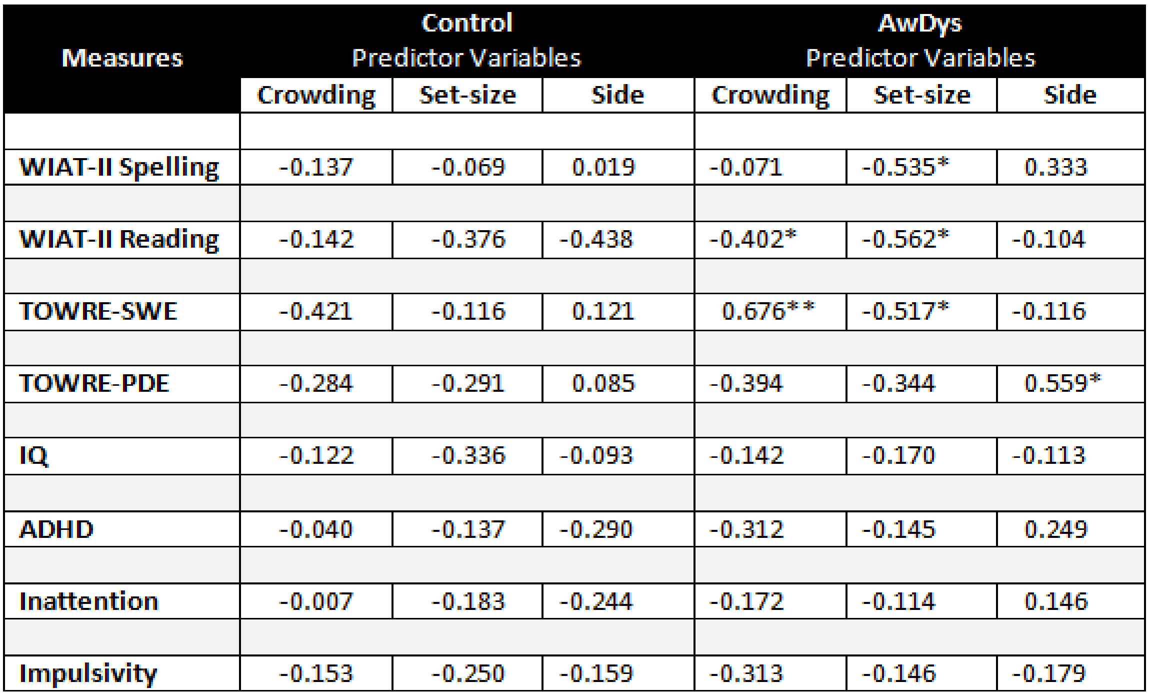
Figure C: Line graph comparing performance accuracies for both groups plotted as a function of set-size. Measures: ANOVA (left) vs. ANCOVA (right). Error bars = ±1 standard error of the mean percentage response accuracy.

7.4. Relationship between Crowding, Set-size and Asymmetric Attention with Literacy

7.4.1 Partial Correlation Analyses

The estimated predictor variables from **section 4.5.5** was used in correlation analyses (*n* = 34 in all cases, approximate critical value of *r* for a two-tailed 5% confidence level = 0.38), with the only exception of not controlling for the influence of ADHD. **Table Z** summarises the values of Pearson's *r* values.

Table Z: Correlation matrix highlighting the relationship between the effects of crowding, set-size and display side on measures of literacy (spelling, reading, TOWRE-SWE and TOWRE-PDE), IQ and ADHD (including subtypes). Values of Pearson's r are shown with * indicating p < 0.05 and ** indicating p < 0.001.



Measures	Control Predictor Variables			AwDys Predictor Variables		
	Crowding	Set-size	Side	Crowding	Set-size	Side
WIAT-II Spelling	-0.137	-0.069	0.019	-0.071	-0.535*	0.333
WIAT-II Reading	-0.142	-0.376	-0.438	-0.402*	-0.562*	-0.104
TOWRE-SWE	-0.421	-0.116	0.121	0.676**	-0.517*	-0.116
TOWRE-PDE	-0.284	-0.291	0.085	-0.394	-0.344	0.559*
IQ	-0.122	-0.336	-0.093	-0.142	-0.170	-0.113
ADHD	-0.040	-0.137	-0.290	-0.312	-0.145	0.249
Inattention	-0.007	-0.183	-0.244	-0.172	-0.114	0.146
Impulsivity	-0.153	-0.250	-0.159	-0.313	-0.146	-0.179

When comparing these associations across groups (**Table Z**), unlike AwDys, the controls did not show any significant correlation towards the psychometric or literacy measures. This might have been due to the smaller spread of performances, probably reflecting the achievement of a near-optimal spelling, word and nonword reading strategy. Interestingly, AwDys showed quite a significant correlation when concerning effects of crowding, on reading (*r* = -0.402, p = .038) and TOWRE-SWE (*r* = -0.676, p < .001) ability; set-size, on spelling (*r* = -0.535, p = .022), reading (*r* = -0.562, p = .015) and TOWRE-SWE (*r* = -0.517, p = .028) ability; and to some extent on the influence of VF on TOWRE-PDE (*r* = 0.559, p = .046) ability. **Figure D** (repeated for convenience) shows a scatter plot highlighting some of these relationships, with literacy scores increasing significantly as the influence of the predictor variables decreased. The association between all three predictor variables and the IQ measure for both groups were not statistically significant. Despite having controlled for potential effects of IQ using a second batch of partial correlations, the findings yielded a similar pattern of results to the aforementioned, which further goes to suggest that the effect of crowding, set-size and VF impacted spelling and/or reading performance directly independent of general cognitive ability (also given that the fact that both groups tested were closely matched for IQ). Furthermore, both groups did not show any significant correlations between literacy and ADHD (along with its subtypes) measures.

7.4.2 Multiple Regression Analyses

Based on the findings from **section 4.1**, all three variables (crowding, set-size and VF effects) turned out to be crucial predictors of spelling, reading, TOWRE-SWE and TOWRE-PDE ability for AwDys, unlike controls. These three measures were then entered as predictor variables of the four literacy measures in a multiple regression analysis (on a group by group basis) to further assess the unique variance of each predictor.

When comparing these associations within different groups, the correlation confers strongly for AwDys, but not controls. For controls, although the equivalent regression analysis for spelling revealed that the predictors explained 14.7% of the variance (adjusted R^2 = .064), neither did the crowding [β = 0.136, t(14) = 0.447, p = .663], set-size [β = 0.030, t(14) = 0.099, p = .923], nor VF [β = -0.044, t(14) = -0.151, p = .882] measures turn out to be significant unique predictors. With regards to reading, the predictors explained 32.2% of the variance (adjusted R^2 = .153) but neither did the crowding [β = 0.046, t(14) = 0.182, p = .859], set-size [β = -0.372, t(14) = -1.492, p = .161], nor VF [β = -0.431, t(14) = -1.785, p = .100] measures turn out to be significant unique predictors. With regards to TOWRE-SWE, the predictors explained 24.5% of the variance (adjusted R^2 = .057) but neither did the crowding [β = -0.495, t(14) = -1.853, p = .089], set-size [β = 0.269, t(14) = 1.020, p = .328], nor VF [β = -0.047, t(14) = -0.184, p = .857] measures turn out to be significant unique predictors. Same was true with TOWRE-PDE whereby crowding [β = -0.437, t(14) = -1.649, p = .125], set-size [β = 0.418, t(14) = 1.602, p = .135], and VF [β = 0.144, t(14) = 0.569, p = .580] measures were not significant unique predictors, despite explaining 25.8% of the group variance (adjusted R^2 = 0.073).

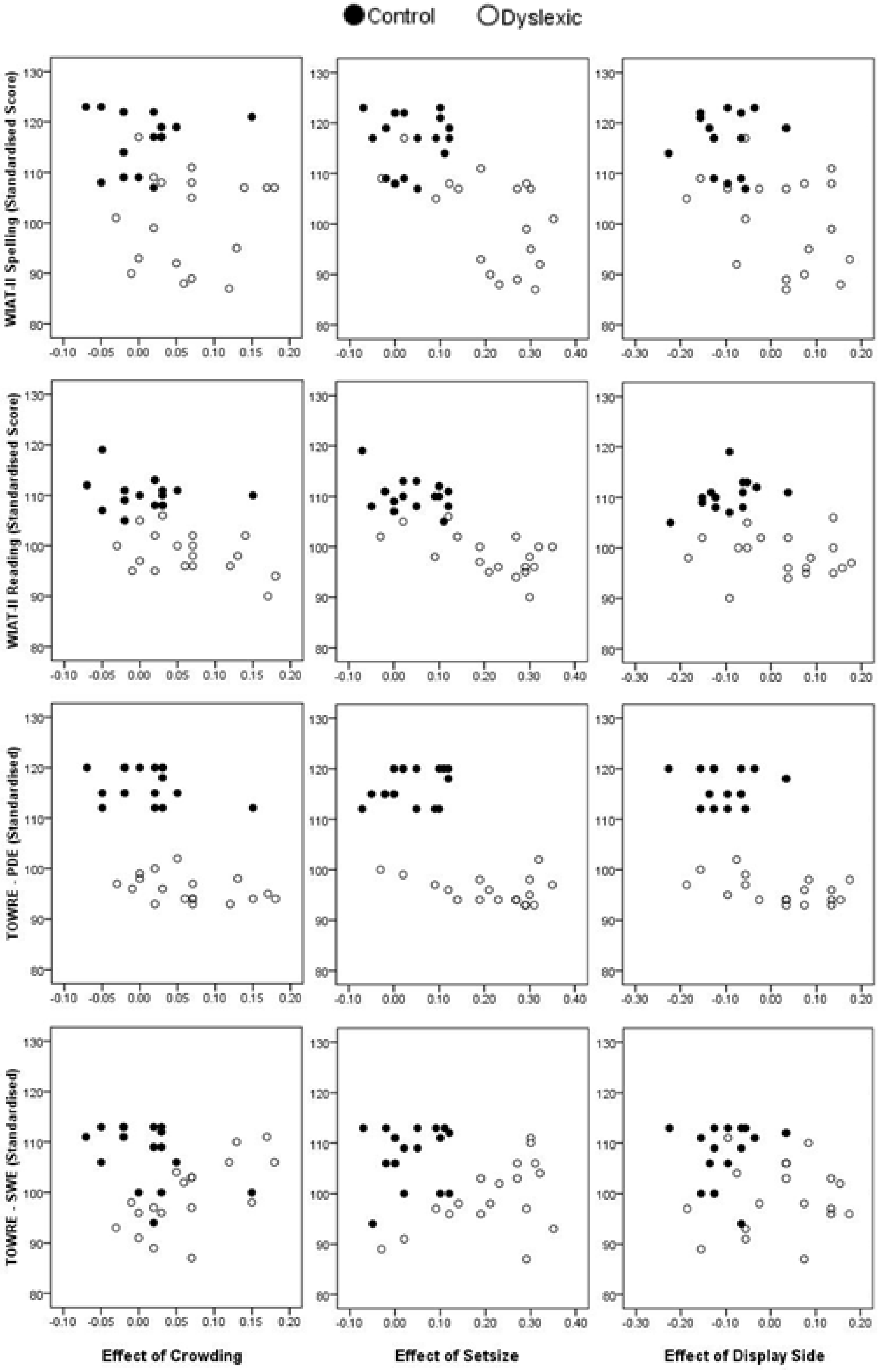


Figure D: Scatter plots showing relationship between measures of WIAT-II Spelling, Reading, TOWRE-PDE and TOWRE-SWE achieved by controls (filled dots) and AwDys (empty dots) as a function of crowding (left panel), set-size (middle panel) and display side (right panel) effect. The effect of crowding reflects the performance difference between crowded vs. spread conditions whilst that for set-size and display side, the performance difference being set-size zero vs. set-size eight conditions.

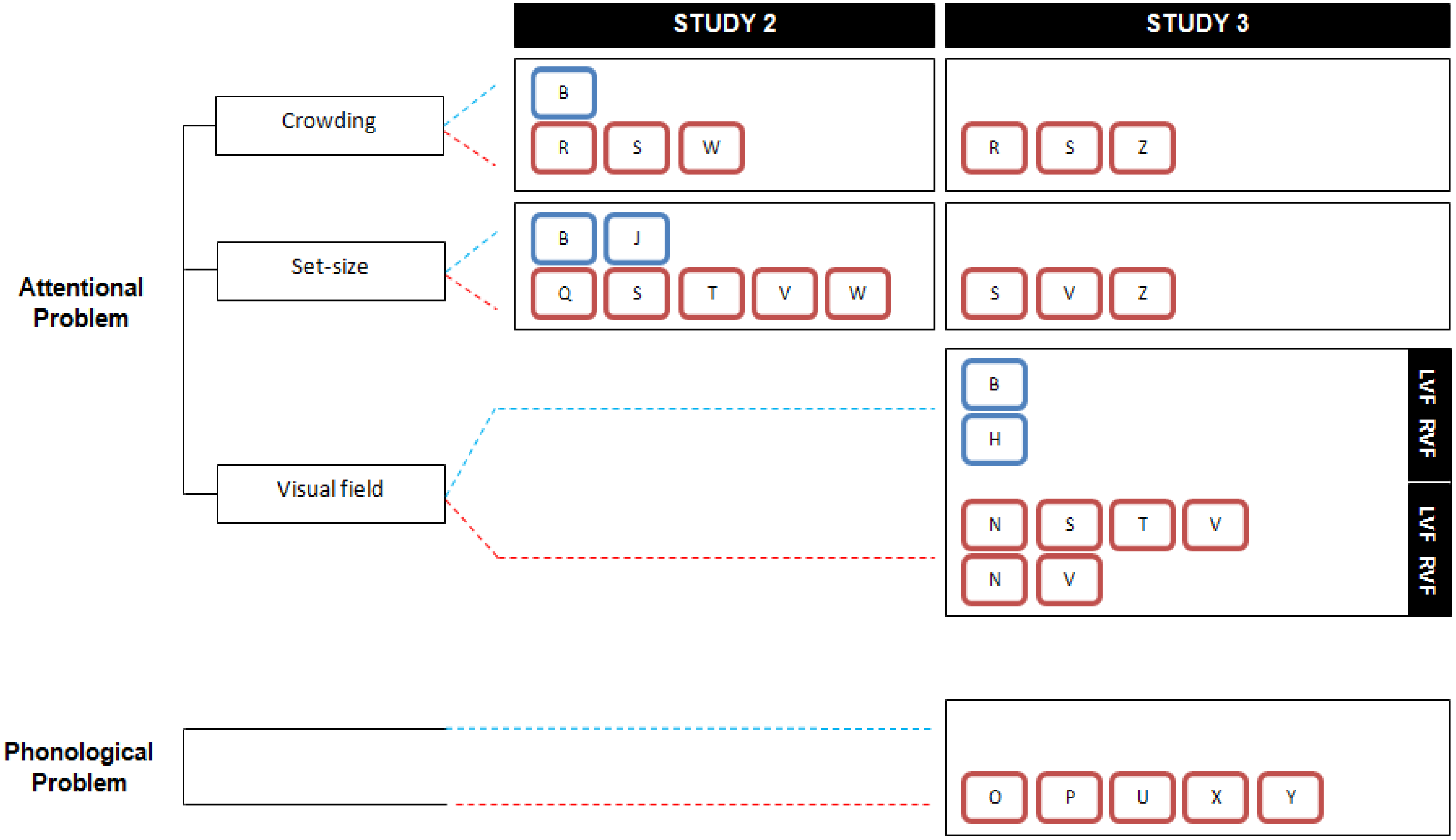
For AwDys, although the equivalent regression analysis for spelling revealed that the predictors explained 35.2% of the variance (adjusted R^2 = .213), both crowding [β = 0.200, t(12) = 0.878, p = .395] and VF [β = 0.144, t(12) = 0.622, p = .544] measures did not turn out to be significant unique predictors with the exception of set-size [β = -0.543, t(12) = -2.279, p = .039]. With regards to reading, the predictors explained 38.5% of the variance (adjusted R^2 = .254) accounting for significant unique variance for just set-size [β = -0.498, t(12) = -2.145, p = .049], unlike crowding [β = -0.268, t(12) = -1.210, p = .246], and VF [β = -0.023, t(12) = -0.100, p = .922]. With regards to TOWRE-SWE, the predictors explained 58.5% of the variance (adjusted R^2 = .496) accounting for significant unique variance for just crowding [β = 0.594, t(12) = 3.260, p = .006], unlike set-size [β = 0.337, t(12) = 1.769, p = .099] and VF [β = -0.073, t(12) = -0.396, p = .698]. With regards to TOWRE-PDE, the predictors explained 41.3% of the variance (adjusted R^2 = .287) accounting for significant unique variance for just VF [β = 0.476, t(12) = 2.162, p = .048], unlike both crowding [β = -0.420, t(12) = -1.938, p = .073] and set-size [β = -0.085, t(12) = -0.375, p = .713].

Note:

The findings repeated using ANOVA in this section demonstrates a similar pattern of results obtained via ANCOVA analyses (**section 4.5.2**).

APPENDIX 8

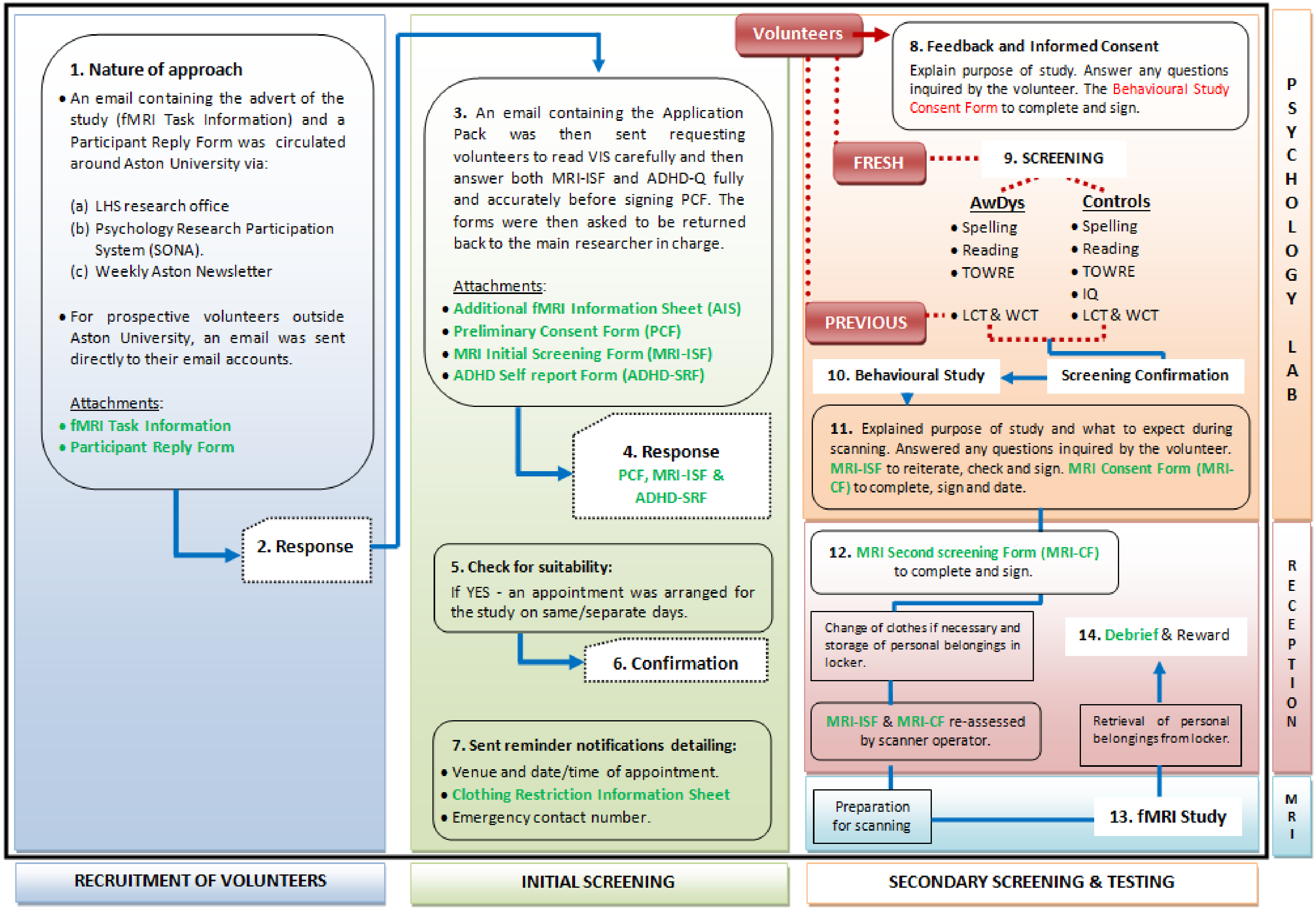
Sub-group classification based on Individual differences across task condition



Note: 11 controls (labelled alphabetically A – J) and 13 AwDys (labelled alphabetically N – Z) comprised of the study sample, with participants divided into either attention or phonology subgroups in accordance to their frequency of deficits. E.g. 3 controls (participants B, H and J) exhibited deficits within separate attentional tasks (although a participant like B who also showed multiple attentional deficits unlike H) thereby confining to the attentional subgroup.

APPENDIX 9

Flowchart of Study 4 procedures



1. Nature of approach

- An email containing the advert of the study (fMRI Task Information) and a Participant Reply Form was circulated around Aston University via:

(a) LHS research office
(b) Psychology Research Participation System (SONA).
(c) Weekly Aston Newsletter

- For prospective volunteers outside Aston University, an email was sent directly to their email accounts.

Attachments:
- fMRI Task Information
- Participant Reply Form

3. An email containing the Application Pack was then sent requesting volunteers to read VIS carefully and then answer both MRI-ISF and ADHD-Q fully and accurately before signing PCF. The forms were then asked to be returned back to the main researcher in charge.

Attachments:
- Additional fMRI Information Sheet (AIS)
- Preliminary Consent Form (PCF)
- MRI Initial Screening Form (MRI-ISF)
- ADHD Self report Form (ADHD-SRF)

5. Check for suitability:
If YES - an appointment was arranged for the study on same/separate days.

7. Sent reminder notifications detailing:
- Venue and date/time of appointment.
- Clothing Restriction Information Sheet
- Emergency contact number.

8. Feedback and Informed Consent
Explain purpose of study. Answer any questions inquired by the volunteer. The Behavioural Study Consent Form to complete and sign.

9. SCREENING

AwDys	Controls
• Spelling	• Spelling
• Reading	• Reading
• TOWRE	• TOWRE
	• IQ
• LCT & WCT	• LCT & WCT

11. Explained purpose of study and what to expect during scanning. Answered any questions inquired by the volunteer. MRI-ISF to reiterate, check and sign. MRI Consent Form (MRI-CF) to complete, sign and date.

12. MRI Second screening Form (MRI-CF) to complete and sign.

Change of clothes if necessary and storage of personal belongings in locker.

MRI-ISF & MRI-CF re-assessed by scanner operator.

Retrieval of personal belongings from locker.

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