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Working out how working memory works: evidence from typical and atypical development

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Abstract

Working memory is an extremely influential concept within experimental psychology, with, at the time of writing, over 90 papers with this term in their title published in this journal alone since 2000. One reason for this interest is that measures of working memory tend to be strong correlates of important indices of real world function. In addition, at first sight working memory appears to be a relatively simple concept to understand. However, despite this apparent simplicity, explaining working memory performance is not straightforward. In this paper I address this challenge, with a particular focus on the development of working memory performance in children; both children developing typically and those experiencing atypical development. I specifically highlight the multiple constraints on working memory performance, and how these constraints inter-relate. I then consider the broader theoretical implications of each of these constraints for current accounts of working memory and its development.

Working out how working memory works: evidence from typical and atypical development

Working memory can be defined as the ability to hold in mind information, in the face of potential distraction, in order to guide behavior (Kane, Bleckley, Conway, & Engle, 2001), and is therefore thought to play an important role in goal-directed action and in learning. Consistent with this, measures of working memory relate to higher-level abilities including intelligence in adults (e.g., Conway, Kane, & Engle, 2003), and aspects of academic achievement in children (De Smedt et al., 2009; Nevo & Breznitz, 2011; Swanson, 2011). There are therefore important practical reasons, in addition to obvious theoretical benefits, for seeking to properly understand working memory function, and for examining how this develops in children.

However, such an understanding requires at least some degree of clarity over the scope of reference of the term 'working memory'. Although a number of theorists would question whether one needs to draw a strong distinction between systems that support immediate or longer-term recall, preferring a unitary model of memory (Brown, Neath, & Chater, 2007; Nairne, 1990; see also Farrell, 2012), psychologists since James (1890) have highlighted the particular status of information that can variously be described as being at the forefront of one's mind, consciously accessible, or within some focus of attention (see Cowan, 1995, Oberauer, 2009). The fact that this information is maintained in an active state implies that working memory has a 'storage' aspect to it. However, while this might suggest equivalence between short-term memory and working memory – and indeed the two are sometimes used interchangeably in the literature – the term working memory carries a sense of updating, manipulation, and control that goes beyond short-term storage (Engle, Tuholski, Laughlin, & Conway, 1999; Jarrold & Towse, 2006). Indeed, arguably the most popular and accepted current measure of working memory is the complex span task (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; see Conway et al., 2005). In this paradigm, participants are presented with a series of to-be-remembered items, but these are interspersed with periods of potentially distracting processing. Consequently, although

performance on such a task does depend on an individual's ability to maintain information in order (the dot totals), it is also potentially affected by their processing efficiency (Case et al., 1982) and by their ability to resist the distraction that this interleaved processing activity generates (Engle, 2002). My main aim in this paper is to better understand these potential constraints on working memory, their interplay, and the psychological processes that underpin them. I do so with a particular focus on my own areas of expertise, notably the development of working memory performance in both typically- and atypically-developing individuals.

Although this analysis is necessarily predicated on the assumption that working memory and long-term memory can be meaningfully dissociated, an important question for researchers in this area is the extent to which these two systems also interact. For example, individuals' ability to recall information in immediate memory tasks is known to be affected by their familiarity with the stimuli (Brener, 1940), and similar effects have been seen in complex span tasks (Conlin & Gathercole, 2006). In other words, existing long-term knowledge is a potential constraint on working memory performance. Conversely, working memory may serve as a mental workspace, allowing for the temporary maintenance of information that can be bound together into learnt, longer-term representations (see Baddeley, Gathercole, & Papagno, 1998; Page & Norris, 2009). As a result, individual or developmental differences in the functions that determine working memory capacity may constrain aspects of longer-term learning. These two types of interaction with long-term memory are not the focus of this paper (for a full discussion see Thorn & Page, 2008) but the latter serves to re-emphasise the importance of searching for a full understanding of working memory function, and its development.

1. What are the key constraints on working memory performance?

In 1974 Alan Baddeley and Graham Hitch published their account of "a working memory system which plays a central role in human information processing" (Baddeley & Hitch, 1974, p.

85). Although described as 'a system', this paper made clear that working memory was multiply determined, reflecting a trade-off between the storage and processing demands of any working memory task. Working memory for verbal material was assumed to rely on the conjoint functioning of a phonemic 'buffer' or 'loop' and a 'central' (or 'executive') component. The subsequent Baddeley (1986, 1992) model made explicit these distinctions, proposing a series of specific subcomponents that collectively support working memory performance: a phonological loop that supports the short-term maintenance of verbal information, a comparable visuo-spatial sketchpad for maintaining visual or spatial material, and a coordinating central executive.

Although fundamentally different accounts of working memory have been proposed, some of which take a more domain-general view of working memory capacity (e.g., Cowan, 1995; Engle, 2002; Jones, Beaman, & Macken, 1996; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; see below for further discussion), the Baddeley model remains highly influential. If one were to take the Baddeley (1986) model as a starting point, one would expect working memory tasks to draw, perhaps to varying extents, on at least two abilities: the ability to maintain information in correct serial order (with an additional distinction between the maintenance of verbal and visuo-spatial material in the phonological loop and visuo-spatial sketchpad respectively), and whatever ability is captured by the central executive. Although Baddeley and Hitch (1974) highlighted the basic processing demands of working memory tasks, even in this model the central component was associated with higher-order control functions such as the setting up of rehearsal plans and retrieving information from the phonemic loop. Subsequent versions of this model have continued to emphasise the coordinating or controlling nature of the central executive, distinguishing it from the more passive 'slave systems' (the phonological loop and visuo-spatial sketchpad) that support short-term storage (Baddeley, 1986, 1993, 1996).

This may well be appropriate (though see next section), but at the same time it is clear that individuals' ability to carry out the basic processing demands of a working memory task does constrain their performance, and potentially in ways that are not executively demanding. For

example, in Case et al.'s (1982) counting span task participants were shown a series of cards, each containing a number of dots that had to be counted. These separate totals had to be held in mind in order to be recalled in correct serial order at the end of the task, and in this way storage demands (maintaining these totals) and processing demands (counting the dots on the current card) were interleaved. Case et al. found a strong correlation between a separate measure of individuals' counting speed and their span on this task, and in a subsequent experiment removed the span differences between adults and 6-year-olds by asking adults to count using a novel (but pre-learnt) set of 'nonsense numbers' that reduced their counting speed to that of these children.

In a similar vein, Russell, Jarrold, and Henry (1996) measured complex span performance among children with autism and typically developing controls using two versions of a counting span task; in a simple version the dot stimuli were presented in canonical forms of the kind shown on dice, and in a complex version they were randomly distributed among additional distractors. Although we expected individuals with autism to be particularly adversely affected by an increase in distractor complexity, given evidence of executive difficulties associated with the condition (see Kenworthy, Yerys, Anthony, & Wallace, 2008), children with autism were actually *less* affected than controls by this difficulty manipulation. However, subsequent work by Jarrold and Russell (1997) showed that individuals with autism were less likely than controls to perceive the canonical dot representations as immediate indicators of numerosity, and so 'counted' these stimuli more slowly than controls. This led to a reduction in the relative difference between counting speeds for the simple and difficult stimuli, which in turn explained the reduction in the effect of this manipulation for this group when embedded in a counting span paradigm.

These findings serve to show that the speed with which participants in complex span tasks can carry out the interleaved processing demands of these tasks is an important constraint on working memory performance. If one accepts that the central executive of working memory (if such a thing exists) operates to *control* storage activities, then one would not want to ascribe to it any role in the completion of relatively basic processing operations within working memory. In other words, the

central executive is a theoretical construct invoked to account for the need to resist the effects of potentially distracting processing episodes within working memory tasks, not to carry out that processing; this distinction has not always been as clearly drawn as it needs to be. Indeed, I suggest that most accounts of working memory need to acknowledge the additional importance of processing speed on performance (see Barrouillet, Bernadin, & Camos, 2004, Fry & Hale, 2000; Mella, Fagot, Lecerf, & Ribaupierre, 2015). For example, if one were to extend the Baddeley (1986) model, one might want to argue for three, rather than two, subcomponents of working memory. These would be the ability to maintain information in correct serial order (served by either the phonological loop or the visuo-spatial sketch pad), the ability to control storage in order to resist distraction from processing (the function of the central executive), and the ability to carry out the processing activity that gives rise to this distraction in the first place (see Magimairaj & Montgomery, 2012). Having said this, the latter presumably depends heavily on an individual's general speed of processing, and so also extends beyond working memory function. In other words, although processing efficiency would certainly be expected to affect working memory performance, and so needs to be considered in any account of such performance, it would be unwise to see it solely as a fundamental 'component' of any working memory system.

2. Empirical support for the claim that working memory performance is multiply determined

The above discussion has already highlighted the need to distinguish general speed of processing from the short-term storage of information in working memory. In addition, there is long-standing evidence to support the potential separability of the short-term storage of verbal as opposed to visuo-spatial information. This comes from the selective effects of verbal versus visuo-spatial distraction on participants' serial recall of such material (e.g., Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Logie, Zucco, & Baddeley, 1990), and in our own work we have shown patterns of apparently selective disruption of either verbal or visuo-spatial short-term memory in individuals

experiencing atypical development. For example, Jarrold, Baddeley, and Hewes (1999) compared the verbal and visuo-spatial short-term memory abilities of individuals with either Down syndrome or Williams syndrome. Verbal short-term memory was measured with a standard digit span test. Visuo-spatial short-term memory was assessed using the analogous Corsi span task, in which the participant has to copy a sequence of spatial actions after seeing this first demonstrated by the experimenter. Once group differences in standardised measures of more general verbal and non-verbal abilities had been accounted for, individuals with Down syndrome were impaired on the digit span task relative to both individuals with Williams syndrome and a control group of children with 'moderate learning difficulties' (MLD). In contrast, a comparable analysis showed that Williams syndrome participants were selectively impaired on the Corsi span task.

This appears to support the suggestion of a double dissociation in short-term memory impairments in these two clinical populations (see Wang & Bellugi, 1994). However, subsequent work from our group suggests that the difficulties that individuals with Williams syndrome experience in tests of visuo-spatial short-term memory may not be any more marked than would be expected given their acknowledged difficulties in all areas of visuo-spatial cognition (Jarrold, Baddeley, & Phillips, 2007). Stronger evidence for a selective deficit in short-term memory function comes from Down syndrome, where many studies have shown that individuals perform more poorly on tests of immediate serial recall of verbal material than would be predicted given individuals' general levels of verbal ability (see Jarrold, Purser, & Brock, 2006). The clearest evidence of this dissociation that we have observed comes from a study by Brock and Jarrold (2005). In this experiment individuals with Down syndrome were compared to typically developing children on two short-term memory tasks. Both were presented on a touchscreen and both involved the participants giving their response by touching a series of locations on this screen (see Figure 1). However, in the verbal task participants had to order these responses on the basis of their short-term memory for verbal material, as they had to touch numbers on the screen to recreate, in correct order, a digit sequence they had just heard. In the spatial task they recreated a spatial

sequence that had just been demonstrated to them. Despite this close matching of response modes, which was designed partly to remove any confounding effects of speech production problems known to be associated with the condition, individuals with Down syndrome were selectively impaired on the verbal short-term memory task.

Further evidence for the multi-component nature of working memory comes from the study of individual differences. In particular, Bayliss, Jarrold, Gunn, and Baddeley (2003) showed that short-term memory (either verbal or visuo-spatial), and general speed of processing were dissociable constraints on both children's and adults' complex span performance. Bayliss and colleagues designed four complex span tasks, formed by the crossing of two processing modes (verbal or visuo-spatial) with two storage conditions (verbal or visuo-spatial) (see Maehera & Saito, 2007; Shah & Miyake, 1996). In all four tasks participants were presented with a touchscreen display showing nine different coloured circles, each containing one of the digits 1 to 9 (see Figure 2). In the two complex span tasks involving verbal processing the participant then heard an object name (e.g., "banana") and had to locate the circle of the corresponding colour (in this case, yellow). In the task that combined verbal processing with verbal storage they then remembered the digit shown in that circle, before the screen refreshed and further verbal processing and verbal storage phases followed. At the end of the trial they attempted to verbally recall the list of digits they had selected in correct serial order. In the task that combined verbal processing with visuo-spatial storage they selected the target circle in the same way, but then remembered its position. Recall at the end of the trial then involved sequentially touching the list of selected positions in correct serial order. The two complex span tasks involving visuo-spatial processing differed in requiring the participant to detect the 'target circle' on the basis of a subtle visual feature; on each sub-episode of the trial one of the nine coloured circles was shown with a hard-to-detect beveled edge. Once the participant had scanned the display and located this target they then remembered the digit within it (visuo-spatial processing and verbal storage) or its spatial position (visuo-spatial processing and

visuo-spatial storage). The trial then continued, again leading to eventual recall of either the list of digits or the sequence of spatial locations.

In addition, Bayliss et al. (2003) also measured participants' ability to complete both the processing and storage components of these tasks in isolation. In two speed of processing tasks participants either heard object names and had to touch the correspondingly coloured circle (verbal processing), or had to search the display to find and touch the one circle with a beveled edge (visuo-spatial processing). In neither case were there any memory requirements in these additional tasks. Similarly, verbal and visuo-spatial short-term memory skills were measured in the absence of any processing demands by presenting digit lists to be recalled, or by flashing a series of spatial locations on the touchscreen ('simple span' versions of the verbal and visuo-spatial storage components of the complex span tasks).

As a result, Bayliss et al. (2003) were able to perform an exploratory factor analysis on children's (Experiment 1) or adults' (Experiment 2) performance across the four complex span tasks, the two independent measures of the processing requirements of these complex span tasks, and the two simple span measures of their short-term storage demands. In both cases a three-factor structure emerged, with one factor drawing on those tasks (either complex or simple) involving verbal storage, another linked to performance on those tasks (again, either complex or simple) including visuo-spatial storage, and the third associated with both independent measures of processing and (to varying degrees) the complex span tasks. In other words, this individual differences analysis fully supported the view that two of the key constraints on working memory performance are short-term storage (which in turn can be dissociated into verbal and visuo-spatial sub-components), and domain-general speed of processing. It therefore provided some support for the Baddeley (1986) model of working memory and poses a potential challenge for single-resource accounts of working memory. At the same time, it re-emphasises the importance of speed of processing on a constraint on working memory performance, something that does not feature directly in the Baddeley account. More broadly it serves to show that variation in working memory

performance can arise from a number of different sources, with the implication that measures of working memory should seek to capture, and potentially distinguish, these components (see Archibald & Gathercole, 2007; Magimairaj, Montgomery, Marinellie, & McCarthy, 2009).

3. Searching for the central executive

While these initial results from the Bayliss et al. (2003) study support aspects of the Baddeley model of working memory, they also reinforce the fact that general speed of processing is not synonymous with executive control. Rather, for there to be meaningful variance in working memory that is reflective of the functioning of the central executive, and of its role in resisting the effects of distraction to storage caused by processing, this would need to emerge over and beyond the basic contributions of speed of processing and short-term memory capacity (see Engle et al., 1999). A recent study by Dang, Braeken, Colom, Ferrer, and Liu (2015) is directly relevant to this argument as these authors measured working memory performance in a large adult sample using a series of complex span tasks, and also gave participants additional measures of processing speed and short-term memory capacity. Dang et al.'s aim was to examine the extent to which working memory performance related to indices of crystallised and fluid intelligence once the contributions of processing speed and short-term memory had been accounted for. However, although processing speed and storage capacity themselves accounted for meaningful proportions of variance in intelligence, there was no reliable additional contribution of working memory capacity. Dang et al. (2015) noted that this does not preclude the possibility that working memory tasks measure more than just processing efficiency and short-term storage capacity, but concluded that their study showed no evidence for any additional (potentially executive) factor driving the relationship between working memory performance and intelligence.

While Dang et al.'s approach certainly reflects an appropriate way of examining the potential contributions of any executive variance in working memory performance, their processing speed

tasks did not directly measure participants' ability to complete the specific processing operations that featured within their complex span tasks. One might argue that one measure of processing efficiency should correlate well with any other, given the argument that variation in speed of processing reflects a relatively low level or primitive cognitive constraint (Anderson, 1992). However, the Bayliss et al. (2003) study is arguably much better placed to answer the question of whether complex span tasks measure more than the sum of their parts, as the independent assessments of processing efficiency and storage capacity employed in that work were exactly matched to the processing and storage components of each complex span task. Despite this, even when they accounted for the independent contributions of speed of processing and short-term memory capacity, Bayliss et al. (2003) found a number of reliable correlations between the remaining variation in complex span performance and measures of academic attainment and intelligence (see also Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005). Furthermore, a subsequent analysis examined the inter-relation of this residual variance (the variance in complex span left once variation in processing efficiency and storage capacity had been controlled for) across the four complex span tasks, finding a reasonable degree of inter-correlation (Jarrold & Bayliss, 2007).

These results imply that the 'residual variance' extracted by Bayliss et al. (2003) is more than just measurement error, and instead captures a crucial aspect of complex span performance (Engle et al., 1999). Indeed, because complex span is – at one level – nothing more than interleaved episodes of processing and storage activity, this residual variance must arise from the need to combine these two components within a single task. This could, of course, reflect the control functions associated with the central executive within the Baddeley model. In our recent work we have been testing this possibility, and also asking exactly what this residual variance does represent.

To that end, a study by Hall, Jarrold, Towse, Zarandi, and Mackett (2016) extended the Bayliss et al. (2003) approach in order to extract the residual variance in children's complex span that remained once independent measures of the ability to carry out the processing and storage components of this task had been accounted for. Hall et al. also included a series of other measures

that we suspected might be associated with this residual variance. These included indices of

children's speech rate, measured as a proxy for rate of subvocal rehearsal (see Standing & Curtiss,

1989) and a measure of the rate at which individuals forgot information while distracted by

processing. Both of these variables were reliably related to the residual variance in complex span.

The role of rehearsal within working memory, and in children's working memory in

particular, will be discussed in the following section. Here I focus on the relevance of a relationship

between residual variance in complex span and individuals' rates of forgetting. This relationship

has also been observed in two previous studies by our group (Bayliss & Jarrold, 2015; Hall, Jarrold,

Towse, & Zarandi, 2012). In the first of these, Bayliss and Jarrold (2015) measured children's

working memory using two complex span tasks, and also administered separate measures of the

processing and storage components of these complex span tasks so as to extract residual variance in

working memory performance. Rate of forgetting was examined in two other tasks, both of which

employed a Brown-Peterson style design (Brown, 1958; Peterson & Peterson, 1959). In each case,

children were first given a list of three nouns to remember. They then performed either 4 or 8s of

continuous distraction before being asked to recall the initial list of words. The distraction phase of

each forgetting task involved the presentation of a screen that contained 9 different coloured circles

(cf. Bayliss et al., 2003) (see Figure 3). In the 'colour' forgetting task the participant heard a series

of colour words, and simply had to touch the circle of that colour on each occasion; once a response

had been made the next colour word was presented, until the specified distraction period had

elapsed. In the 'object' forgetting task the distraction phase was similar, but involved the

presentation of a series of object names. In this case the participant's task was to touch the circle

whose colour matched that of the object (e.g., yellow for "banana"). These two tasks were chosen

because it was expected that the object forgetting task would lead to more forgetting, by virtue of

the fact that the auditory tokens presented during the distraction phase were nouns of exactly the

same form as those presented in the initial memory encoding phase. As such, if executive control is

required to maintain information in the face of distracting interference, one would expect this to be more apparent in the object than in the colour forgetting task.

Participants did forget information more rapidly in the object forgetting task than they did in the colour forgetting task. In addition, the residual variance in complex span, that remained once individual differences in processing speed and storage capacity had been accounted for, correlated reliably with measures of the rate of information loss in the two forgetting tasks. However, in contrast with our initial predictions the correlation between residual variance and rate of forgetting in the object task was no greater than that between residual variance and rate of forgetting in the colour task. In other words, residual variance in complex span is related to the rate at which children forget information when occupied by distraction. However, it appears that this variation in forgetting rate is not related to the extent to which individuals can exert *executive* control over the interfering effects of distraction. This is shown by the fact that this relationship appears to be insensitive to the extent of representational similarity (see Saito & Miyake, 2004), and hence interference, between the distracting activity and the memoranda.

4. The role of rehearsal in working memory performance and development

As noted above, in addition to variation in the rate at which individuals forget information due to distraction, there may also be variance in the extent to which individuals make use of, or benefit from, rehearsal to maintain information in working memory. Although the concept of rehearsal has been integral to Baddeley's working memory model since its inception, researchers are beginning to question its utility as an explanatory construct. In addition, many have argued that young children do not engage in spontaneous rehearsal to maintain information in working memory. Clearly if rehearsal is to be of any use in explaining children's working memory performance one needs to be confident that rehearsal supports memory performance, and that young children can make use of it.

The first of these claims has been recently challenged by Lewandowsky and Oberauer (2015) who argue that rehearsal is necessarily poorly equipped to maintain information during a delay. They point out that any attempt at rehearsing a list carries with it the possibility of making an error during the subvocal repetition of a list; such a claim follows naturally from the fact that serial recall is not error free, and is associated with omission and transposition errors (see Henson, 1998). As a result, rehearsal risks damaging the fidelity of the representation of the to-be-remembered list, with this problem becoming more and more pronounced with every repetition. Indeed, in simulations that sought to model various rehearsal schedules, Lewandowsky and Oberauer (2015) illustrated this problem, showing that rehearsal during a delay can actually impair memory because of the propagation of retrieval errors (see also Burgess & Hitch, 1999). Consequently, although Lewandowsky and Oberauer do not deny that rehearsal takes place, they argue that it is not casually related to individuals' ability to maintain information in working memory. In separate work Oberauer et al. (2012) simulated working memory performance using a computational model that involved no rehearsal of the memoranda.

While Lewandowsky and Oberauer (2015) are undoubtedly correct to highlight the problem of error propagation due to rehearsal of lists that are beyond a participant's span, the risk of an individual making such errors is dramatically reduced for lists that are well within their capacity. For example, although one would certainly expect errors to occur if a typical adult participant attempted to rehearse a list of 8 or 9 words, one might equally expect perfect rehearsal – even over a very long period – of lists of 2 or 3 words (see Tan & Ward, 2008). Rehearsal may therefore serve a useful purpose, and play a causal role in maintaining to-be-remembered information, if individuals selectively use it to maintain lists that are within their recall capacity. Computational models have assumed that participants might rehearse as many items as possible within the time available to them, with their capacity for rehearsal therefore being limited by a combination of their rehearsal rate and the length of any delay interval (Page & Norris, 1998; Lewandowsky & Oberauer, 2015). However, it may well be that the participant's own awareness of their ability to

subvocally repeat a list with a high degree of accuracy is an additional or even more important constraint on their use of rehearsal. For example, Tan and Ward (2008) presented adults with lists of 6 disyllabic words, at varying presentation rates. Serial position curves showed that participants were unable to recall all six items with a high degree of accuracy. However, on average participants showed evidence of rehearsing the first four items on the list when presentation rates were slow enough to allow rehearsal, and at the individual level the length of this 'rehearsal set' correlated with participants' recall performance. Rather than necessarily indicating that rehearsal drives recall, this pattern of findings might instead reflect the impact of individuals' recall capacity on their ability to engage in subvocal rehearsal during list presentation.

Support for this suggestion comes from our own work, in this case looking at adults' ability to maintain information during a filled retention interval. Jarrold, Tam, Baddeley, and Harvey (2010) presented typical adults with lists of 6 disyllabic words (similarly to Tan & Ward, 2008) combined with an 18s interval that was filled with one of two types of distraction. During this interval all participants were shown the same stimuli, namely successive pairs of letters, but half of the sample judged whether the two letters in each set rhymed with each other (verbal processing) while the other half judged whether the two letters shared an axis of symmetry (visual processing). In addition, the task was divided into 7 sub-conditions, formed by the systematic 'movement' of the distraction interval within the presentation of the memory list. For example, in one condition that had a Brown-Peterson task structure, all the 6 memoranda were presented before the distraction interval. In another, the first 5 words were presented, followed by the distraction interval, followed by the presentation of the final word. Another condition involved the presentation of the first 4 words, then the distraction, then the final two words, and so on.

The participants who engaged in verbal processing during the distraction interval tended to recall fewer items than those who were asked to carry out visual processing on the same stimuli, potentially because verbal processing precluded subvocal rehearsal. However, this effect was not seen to the same extent in all conditions, and, importantly, was not particularly marked in the

conditions where either 5 or 6 items were presented prior to the distraction phase. In these

conditions participants in the visual processing group struggled to maintain these initial memoranda

during the distraction interval, even though one would assume that they would have been free to

rehearse them. In contrast, when only 4 items were presented prior to the distraction phase a clear

group difference was observed, with individuals in the visual processing group showing good recall

of these initial list items at the end of the task in comparison to the much poorer recall of these

items in the verbal processing group. Jarrold et al. (2010) argued that these results are consistent

with the claim (Tan & Ward, 2008) that adults are able to rehearse 4 dissyllabic words, but struggle

to rehearse 5 such items. Here this effect was observed even though participants in the visual

processing group would certainly have had time to rehearse 5 or 6 items, and so presumably reflects

the capacity limit on rehearsal performance in this latter group.

However, even if one accepts that rehearsal can play a functional role in maintaining

information during a delay, a remaining question is whether young children employ such a strategy.

Within the developmental literature it has long been assumed that children younger than 7 years of

age do not engage in rehearsal to maintain information in working memory (see, Gathercole, 1998).

Although more recent work has lowered this age slightly, the notion that children undergo a

qualitative change in their use of rehearsal in early to mid childhood remains widely held (e.g.,

Henry, Messer, Luger-Klein, & Crane, 2012). However, we have recently challenged this

assumption for two main reasons (Jarrold & Hall, 2013). The first is that much of the previous

evidence taken to support the view that young children do not rehearse can be questioned. This

evidence includes the fact that young children tend not to show a strong association between

measures of speech rate and span (e.g., Gathercole & Adams, 1993; Ferguson, Bowey, & Tilley,

2002), contrary to what is observed in older children and adults (Baddeley, Thomson, & Buchanan,

1975; Jarrold, Cowan, Hewes, & Riby, 2004). In addition, young children tend not to show reliable

effects of word length and phonological similarity for visually presented material (e.g., Allik &

Siegel, 1976; Henry et al., 2012), which in turn implies that information may not be being recoded

and rehearsed in a phonological form (see Howard & Franklin, 1990). However, the data on children's speech rate-span correlations are more equivocal than is often thought (Jarrold & Hall, 2013), and such correlations may be particularly 'noisy' in young children. In addition, a reduction in the size of the word length and phonological similarity effects to non-significant levels in young children may simply reflect the fact that these effects scale proportionally (Beaman, Neath, & Surprenant, 2008; Logie, Della Sala, Laiacona, Chambers, & Wynn, 1996), and are therefore hard to detect in absolute terms among individuals whose overall recall levels are low (Jarrold, Danielsson, & Wang, 2015; Wang, Logie, & Jarrold, in press). Indeed, we have shown that children younger or older than 7 show comparable effects of phonological similarity for visually presented materials when these effects are analysed in proportional terms (Jarrold & Citroën, 2013).

Our second reason for questioning the view that young children cannot rehearse follows from the suggestion, made above, that rehearsal is constrained by an individuals' recall capacity. Following Laming (2006) (see also Cavanaugh, 1972) we have argued that rehearsal should be understood as just another example of recall, albeit recall that typically occurs subvocally (Jarrold & Hall, 2013). If one accepts this view, then a logical consequence is that individuals will not be able to successfully rehearse lists that they cannot recall. In the context of the development of working memory this means that young children will necessarily not show evidence of rehearsal on lists that are beyond their recall capacity. In turn this has implications for how one might look for evidence of the potential markers of rehearsal in children of different ages. On the one hand, presenting the same number of memoranda to all participants (e.g., Allik & Siegal, 1976) could result in these lists being within the recall (and therefore rehearsal) capacity of older but not younger children. On the other, floor effects may reduce a study's power to find evidence of rehearsal if young children are given shorter lists to remember than older participants (see Jarrold, Cocksey, & Dockerill, 2008).

5. Broader theoretical implications

The previous sections have shown that working memory performance is multiply determined. Given that working memory can be defined as the ability to maintain information in the face of distraction, it is no surprise that two of the major constraints on performance are short-term storage capacity, which supports the maintenance of information, and processing efficiency, which determines the time that individuals take to perform the distracting activity that might be embedded in a task. However, working memory tasks capture more than this, and there remains variance in working memory performance over and beyond storage capacity and processing efficiency. There are a number of candidate causes of this additional 'residual' variance, which in terms of the Baddeley model might potentially be seen as reflective of the functioning of the central executive (see Logie, in press). These include the strategic search of long-term memory (e.g., Unsworth & Engle, 2007a), the ability to switch between the storage and processing components of a working memory task (e.g., Hitch, Towse, & Hutton, 2001), or the possibility of consolidating just-presented information in order to protect it from subsequent interference from the distracting activity (e.g., Bayliss, Bogdanovs, & Jarrold, 2015; Ricker & Cowan, 2014). In this paper, I have focussed on two additional potential sources of residual variance in working memory, namely variation in the rate at which individuals forget when distracted, and variation in the efficiency of maintenance activities such as rehearsal. Not only is there evidence, reviewed above, that working memory tasks do capture these sources of variance, but they arguably parallel each other (Kane & Engle, 2002); individual differences in forgetting rates will become apparent when participants are engaged in distracting activities, while individual differences in the efficiency of maintenance operations will emerge when participants are not occupied by distraction. In sum, I have argued that working memory performance depends on, at the very least, storage capacity, processing efficiency, and the competing effects of variation in rate of forgetting and the efficiency of maintenance mechanisms. The remaining subsections of this paper further unpack the importance of each of these constraints and their theoretical relevance for our understanding of working memory and its development, and

do so in with reference to the broader context of working memory theory that extends beyond the Baddeley model.

Storage capacity

The Baddeley (1986) model very clearly distinguishes between the systems that support the short-term storage of verbal and visuo-spatial information, with the phonological loop and the visuo-spatial sketchpad, respectively, representing distinct components of working memory. However, not all models draw this distinction so clearly (Camos, Lagner, & Barrouillet, 2009; Cowan, 2005) if at all (Farrell, 2012; Jones, Macken, & Nicholls, 2004; Oberauer et al., 2012). At first glance, the considerable evidence of selective disruption of verbal or visual short-term storage by the corresponding form of distractor task (see above) appears to strongly support the notion of two separate stores. However, if one assumes that secondary tasks disrupt memory by causing interference with the to-be-remembered information, rather than by blocking the particular functions of a specific store, then verbal distraction will necessarily affect verbal more than visuo-spatial memoranda, and vice versa (Oberauer et al., 2012). In addition, there is evidence that the short-term maintenance of both verbal and visuo-spatial information relies on common mechanisms for serial ordering, as shown by similar patterns of recall and error distributions across such tasks (Guérard & Tremblay, 2008; Hurlstone, Hitch, & Baddeley, 2014).

However, while verbal and visuo-spatial storage capacities may develop in tandem in children (Chua & Maybery, 1999), individual differences studies do show that verbal and visuo-spatial serial recall measures are separable in both children (Alloway, Gathercole, & Pickering, 2006) and adults (Kane et al., 2004). In addition, our own work, reviewed above, has shown that specific verbal short-term memory deficits are associated with Down syndrome (see also Archibald & Gathercole, 2007; Laws, 2002). These data imply that, despite apparent commonalities, verbal and visuo-spatial short-term memory performance cannot be reduced to one and the same thing.

One way of reconciling the above points is to suggest that a common serial-ordering process operates on two different representational domains – the verbal and the visuo-spatial. For example Majerus et al. (2010) found common areas of neural activation associated with the short-term storage of both verbal and visual material, which they argued reflected the operation of a domain-general serial-ordering system. At the same time, modality-specific areas of activation were observed in regions typically associated with the processing of either verbal or visual information, which they ascribed to domain-specific processing of the to-be-remembered material (see also Majerus, 2013).

Experimental studies that have addressed the question of whether short-term serial ordering is domain-general or domain-specific have tended to do so by examining whether maintaining ordered information from one domain affects memory for the order of items in another (e.g., Depoorter & Vandierendonck, 2009; Morey & Mall, 2012; Soemer & Saito, 2016; Vandierendonck, 2016; see also Farrell & Oberauer, 2014). These, and related (Logie, Saito, Morita, Varma, & Norris, 2015; Saito, Logie, Morita, & Law, 2008) studies have produced mixed findings, with some authors arguing for domain-specific ordering of verbal vs. visuo-spatial information while accepting that these two mechanism operate on very similar principles (Logie et al., 2015; Hurlstone et al., 2014). However, the current balance of evidence appears to be in favour of at least some degree of domain-general short-term ordering of representations (see Farrell & Oberauer, 2014; Vandierendonck, 2016). If one were to argue that ordering in short-term memory is entirely domain-general, then one would need to question the assumption, made in the classic Baddeley model, of separable verbal and visuo-spatial short-term memory systems (see Vandierendonck, 2016). Indeed, one might go as far as saying that this view removes the need for any form of separation of 'short-term memory' systems, because any apparent domain-specificity in performance simply results from a single memory process operating on representations which are distinct from each other for reasons that are entirely unrelated to their 'memorability' (see Hulme & Roodenrys, 1995; Jones et al., 1996). Although plausible, there remains evidence that verbal short-

term memory deficits in certain developmental conditions are not reduceable to more fundamental language problems (Brock & Jarrold, 2004; Montgomery, 1995; Jarrold, Baddeley, & Phillips, 2002), implying that verbal short-term memory cannot simply be equated to auditory processing coupled with serial ordering. As a result, short-term storage appears to involve domain-specific memory representations that are abstracted from perception to some meaningful degree.

Processing efficiency

Complex span scores are typically lower than simple span scores (Unsworth & Engle, 2007b), indicating that the requirement to carry out an interleaved processing activity during a working memory task does detrimentally affect task performance. While this might not be surprising, there remains considerable debate as to the reason why processing causes forgetting. According to the Baddeley model, distraction prevents maintenance activities; specifically, verbal processing that recruits or interferes with the ability to subvocalise will hamper rehearsal. As a result, memory traces suffer time-dependent trace decay during the processing activity. Under this account it is clear why processing efficiency constrains performance – the quicker verbal distraction can be dealt with the less trace decay occurs.

Direct evidence for the importance of processing speed comes from individual differences studies of the kind reviewed above, but also from experimental manipulations of the complex span paradigm. For example, Towse and Hitch (1995) asked adults to count 'easy' or 'difficult' stimuli in the processing episodes of a counting span task. They increased the number of items that had to be counted in easy stimuli to the point at which these processing episodes lasted the same time as the difficult ones, and found that this equated working memory spans (see also Case et al., 1982; Halford, Maybery, O'Hare, & Grant, 1994; Towse, Hitch, & Hutton, 2002). Related work by Towse and by Saito (Maehara & Saito, 2007; Saito & Miyake, 2004; Saito, Jarrold, & Riby, 2009; Towse, Hitch, & Hutton, 1998, 2000) has shown that processing time effects operate at the level of the trial in complex span tasks. Specifically, trials that begin with a particularly difficult processing

episode which then gives rise to the first to-be-remembered item (and which therefore occurs before any items are held in memory) are easier than trials in which the identical processing episodes are re-ordered so that the particularly difficult episode comes at the end of the trial when the memory load is maximised.

A related, though potentially distinguishable, line of work has been conducted by Barrouillet and Camos, leading to the development of their Time-Based Resource-Sharing (TBRS) account of working memory (Barrouillet et al., 2004; Barrouillet, Portrat, & Camos, 2011). Under this account, any attentionally-demanding processing operations impose a 'cognitive load' that prevents maintenance activities that also draw on these attentional resources, with the consequence that memory representations degrade due to trace decay. Although clearly similar to the Baddeley model, the TBRS account assumes that attention is a central resource, and that maintenance can occur through a domain-general process of attentional refreshment (Raye, Johnson, Mitchell, Greene, & Johnson, 2007). More recently, Barrouillet and Camos have also argued that blocking subvocal rehearsal will, additionally, lead to domain-specific forgetting of verbal memoranda (Barrouillet, & Camos, 2010; Camos et al., 2009) over and beyond the domain-general effects of cognitive load.

Models based on trace decay can therefore relatively easily account for the claim that both the nature *and* duration of processing activity constrain working memory performance. In turn they readily explain the importance of processing efficiency, which directly affects the time taken to complete distracting processing. Models that assume that forgetting from working memory occurs because of interference are also capable of explaining why the nature of any distracting processing affects working memory performance, as the greater the similarity between the memoranda and the distraction, the more forgetting will occur. In contrast, interference accounts might be taken to predict that the duration of any distraction is unimportant, because forgetting is caused by the overlap of representations that occurs at the point of encoding of the interfering distraction (Oberauer et al., 2012; though see Posner & Konick, 1966). Indeed, Lewandowsky, Geiger,

Morrell, and Oberauer (2010) found that varying the length of an unchanging verbal distraction within a complex span paradigm lead to little or no variation in forgetting (see also Hughes, Vachon, & Jones, 2007; Jones, 1994). However, in typical complex span tasks participants are rarely asked to repeatedly process unchanging distraction, but rather are often presented with multiple potentially distracting representations within a single 'processing episode'. As a result, such processing would lead to forgetting that does increase over time (Lewandowsky et al., 2010), though only because a greater processing duration is associated with more processing events. As such, while an interference account can explain the 'apparent' importance of processing duration, it would not obviously lead to the suggestion that greater processing efficiency, which shortens the time over which a fixed number of events are processed, should result in less forgetting.

This might seem to imply that an interference account of forgetting from working memory is incompatible with the evidence of the importance of processing efficiency (i.e., processing speed) outlined above. However, this need not be the case, at least not when working memory tasks are presented in a way that allows free time for maintenance activities once processing operations are completed. Although some experiments have presented self-paced complex tasks, in which presentation of the next to-be-remembered item immediately follows the participants' processing response (see Friedman & Miyake, 2004), most working memory tasks allow a fixed time for processing in between each memoranda, with the consequence that participants who complete processing more rapidly have more free time available in which any maintenance operations might take place (Barrouillet et al., 2004). If one accepts that such maintenance operations can boost memory (see above discussion) then even if processing causes forgetting by interference rather than trace decay, then more efficient processing would allow more time to offset this forgetting.

This raises the question of whether processing speed is collinear with, or rather potentially separable from, the speed of any such maintenance operations. If refreshment rate or rehearsal rate are collinear with speed of processing of distraction, then the efficiency of maintenance could not emerge as a separate additional constraint on working memory performance under this type of

account. This point will be returned to below, but here I note that our own work suggests that the efficiency with which individuals deal with the processing requirements of working memory tasks is closely related to relatively general indices of speed of processing. For example, choice reaction times correlate highly with decision times for processing operations embedded in complex span tasks, Bayliss et al. 2005; see also Kail & Hall, 2001). In addition, we have shown that classroom measures of inattention among typically developing children are more closely correlated with speed of processing than the other components of working memory performance (Jarrold, Mackett, & Hall, 2014). This raises the possibility that other evidence of an association between working memory performance and inattention in the classroom (see Gathercole, Lamont, & Alloway, 2006) may reflect the importance of general speed of processing, which in turn might be closely linked to general intelligence, rather than any potentially executive aspects of working memory

Forgetting rates

Our work, particularly that of Bayliss and Jarrold (2015), has shown that the variance in complex span performance that remains once individual differences in storage capacity and processing efficiency have been accounted for, correlates with the amount of information participants are able to maintain over a filled delay. In other words, the rate at which individuals forget information while occupied is related to residual variance in working memory performance. This is an important finding because it provides a further example of a potentially important constraint on working memory performance. However, at the same time it might seem a somewhat unsurprising argument to advance. Earlier I argued that, in conceptual terms, this residual variance in working memory amounts to variation in individuals' ability to maintain material in the face of distraction. It is therefore arguably tautologous to suggest that this corresponds to the extent to which individuals forget information while distracted.

At the same time, the nature of most working memory tasks, and the complex span task in particular, shows why such a claim is a reasonable one to make. Complex span tasks are, in one

respect, just a series of mini Brown-Peterson tasks strung together (Tehan, Hendry, & Kocinski, 2001), and so it makes perfect sense that the rate at which individuals forget in Brown-Peterson-like tasks is a correlate of complex span performance. One of the important implications of our work is that individual variation in the extent of this forgetting is orthogonal to the amount of information that individuals can maintain in the short-term. The other follows from our finding (Bayliss & Jarrold, 2015) that forgetting rates from a Brown-Peterson task that involved a high level of interference between the pre-load list and the subsequent distraction were no better predictors of residual variance in working memory than were forgetting rates from a Brown-Peterson task that invoked much less of this form of representational-based interference. Although this is a single finding that clearly deserves replication, it does suggest that variation in the extent to which individuals forget information while distracted in a working memory task is not driven by the ability to resist this interference. This poses a potential challenge to the view that individual differences in the executive abilities needed to resist interference mediate complex span performance (Kane et al., 2001). However, it should be noted that claims for this form of executive control are focussed more on the ability to resist proactive interference, by virtue of holding other information active in working memory, than on resisting interference caused by the representational similarity of items within working memory (Kane et al., 2001; Oberauer, Lange, & Engle, 2004).

Given this, variation in forgetting rates within working memory may reflect a non-executive parameter, which we have assumed reflects a more basic susceptibility to distraction. One obvious candidate parameter that would be consistent with the Baddeley model of working memory would be variation in the rate with which individuals suffer trace decay of information. However, it is also possible to favour an interference model of forgetting from working memory, and still explain non-executive variation in the rate at which forgetting occurs. For example, although our data suggest that forgetting *rates* are not related to individuals' ability to *resist* interference, it is still entirely possible that forgetting is caused by interference, with variation in the extent of any forgetting caused by individual differences in some more basic susceptibility to interference parameter. For

example, Towse, Hitch, Hamilton, Peacock, and Hutton (2005) suggested that rather than understanding variation in working memory with a 'suitcase' metaphor that emphasises differences in storage capacity, one might equally employ a 'thermos flask' metaphor that highlights variation in individuals' ability to maintain representations in an active (i.e., 'hot') state. Under this form of account, susceptibility to interference would equate to stable (within the individual) individual differences in the degree of insulation of the thermos flask.

Crucially, such a 'susceptibility' factor would mean that while all individuals would forget more when faced with highly interfering distraction as opposed to less interfering distraction, some individuals would experience more forgetting than others in both cases. Indeed, Oberauer et al. (2012) captured individual differences in performance in their interference-based model of working memory by varying either of two parameters that would be equally implicated in both low and high interference conditions. These were parameters corresponding to i) the extent to which potential candidates for retrieval could be discriminated from each other, and ii) the rate at which distracting information could be removed from working memory. Although neither was couched in terms of the kind of 'susceptibility' factor I have described, this serves to show that the rate of forgetting within an interference-based model can be moderated by factors that are common to all tasks. Indeed, one might argue that 'rate of distractor removal' might well correspond very closely to rate of forgetting due to interference.

Rehearsal

Throughout this paper I have argued that subvocal rehearsal plays a role in maintaining information in working memory when individuals are not distracted by processing activities. However, before exploring the implications of this claim in more detail, it is worth asking whether other processes might also, or instead, support the maintenance of to-be-remembered information in complex span tasks and other working memory paradigms (rehearsal itself might take different forms, from basic repetition of a single item, to rote repetition of a series of items in serial order,

through to elaborative rehearsal that seeks to manipulate the to-be-remembered information in some way, Craik & Watkins, 1973). In particular, and as discussed above, Barrouillet, Camos, and colleagues have argued that domain-general attentional refreshment re-activates memory traces in working memory, perhaps in addition to domain-specific verbal rehearsal processes (see Camos, 2015). It is certainly possible that individuals refresh memoranda during either experimenter-imposed or self-generated intervals between distraction in working memory tasks (Jarrold, Tam, Baddeley, & Harvey, 2011; Vergauwe, Camos, & Barrouillet, 2014). However, and as already noted, for refreshment to emerge as an additional constraint on working memory performance over and above storage capacity and processing efficiency, individual differences in refreshment rate would need to be dissociable from individual differences in general speed of processing (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009).

A number of studies, predicated on the TBRS model, have attempted to equate the cognitive load experienced by children of different ages in working memory tasks. This has been done by varying the number of processing operations that children of different ages need to complete in a certain time interval in order to equate total processing times, and, by implication, total free time, across groups (Barrouillet et al., 2009; Gaillard, Barrouillet, Jarrold, & Camos, 2011; Gavens & Barrouillet, 2004). These studies have still found developmental differences in working memory scores, suggesting that children of different ages do differ in their ability to make use of a fixed amount of free time. However, while these authors have tended to attribute these remaining developmental differences to age-related differences in refreshment efficiency, these findings do not show that refreshment efficiency is dissociable from general speed of processing. Indeed, Gaillard et al. (2011) attempted to equate refreshment rates across age groups by adjusting the ratio of the available free time experienced by younger and older groups to match the ratio of these two groups' processing speeds. This manipulation did eliminate developmental differences, consistent with the view that refreshment rate is, in fact, collinear with general speed of processing.

In contrast, other evidence indicates that rehearsal rates may be dissociable from more basic indices of processing speed. Bayliss et al. (2005) measured children's overt articulation speed for single words as a potential index of their covert rehearsal rate alongside a range of other measures of short-term storage and processing speed. Factor analysis showed that articulation speed loaded on both of two emergent factors that, respectively, captured variance in storage skills and processing speed. The loading on the storage factor occurred even though the articulation task involved repetition of a single word, and so presumably imposed minimal memory demands (Ferguson & Bowey, 2005).   Given this, Bayliss et al., (2005) suggested that the storage factor reflected the *efficiency* of maintenance. In addition these two factors accounted for separable amounts of the age-related variance in complex span, leading Bayliss et al. to conclude that general speed of processing and rate of maintenance of to-be-remembered items were separable influences on working memory development.

Similar results have emerged from our more recent work (Hall et al. 2016), where estimates of processing efficiency and measures of speech rate were again dissociable in individual differences analyses (see also Cowan et al., 1998). In addition, although others have argued that the link between processing speed and short-term storage might be mediated by speech rate (e.g., Kail, 1992), implying that speech rate is very closely related to speed of processing, studies have shown that age-related variance in speech rates cannot be entirely explained by changes in processing speed (Kail, 1992; Kail & Park, 1994; Ferguson & Bowey, 2005), and that processing speed exerts an additional influence on memory span that is independent of speech rate (Ferguson & Bowey, 2005). In other words, although rehearsal rate is unsurprisingly related to general speed of processing, these two constructs appear not to be identical, and may account for separable proportions of the age-related variance in working memory performance.

It is therefore possible that variation in the efficiency with which individuals rehearse as indexed, albeit indirectly, by overt speech rates, corresponds to the maintenance component of the residual variation in complex span that remains once processing speed and storage capacity are

accounted for. If this is the case, then this suggests a radical revision of the Baddeley model of working memory, as it would imply that rehearsal can be dissociated from storage to a greater extent than the phonological loop account would imply. In addition, given evidence that residual variance in complex span is domain-general, one would need to argue that rehearsal is not specific to the verbal domain. Although the latter appears a somewhat counter-intuitive suggestion, if one assumes that rehearsal equates to recall (see above) one might argue that any material that can be recalled can therefore be rehearsed. Under this account visuo-spatial information would be 'rehearsed' simply by being covertly, rather than overtly, recalled (Cortis, Dent, Kennett, & Ward, 2015). Similarly, the claim that rehearsal can be distinguished from short-term storage to a greater degree than the phonological loop account proposes is consistent with work that suggests that storage capacity is most accurately measured by examining individuals' ability to maintain information in tasks that preclude rehearsal (Cowan et al., 2005; Hall, Jarrold, Towse, & Zarandi, 2015).

However, a problem for this position is that the tasks most often used to isolate the storage aspects of complex span, such as digit span tasks, are not of this form. Although one might question the need for rehearsal in immediate serial recall tasks such as digit span (Jarrold & Hall, 2013), if one accepts that rehearsal is essentially a form of recall (see above) such tasks should capture the skills that underpin rehearsal. If so, then covarying out the variance in these measures from complex span performance should prevent any additional index of rehearsal from accounting for remaining, residual, variation.

Given this, one might instead argue that the component of residual variation in complex span that relates to rehearsal behaviour in fact reflects individual differences in the strategic use of rehearsal to maintain information where possible. Although I argued, above, that the view that rehearsal is a form of recall implies that any child can rehearse a list that is within their recall capacity, this does not necessarily mean that a child will elect to engage in rehearsal. The older literature on children's rehearsal behaviour focussed in some detail on the question of whether an

apparent absence of rehearsal in young children reflects a competence (inability to use) or performance (failure to use) deficit (see Flavell, 1970). While I have questioned much of the evidence purporting to show that children younger than 7 do not rehearse, there is work suggesting that young children do not rehearse when they might otherwise do so (Flavell, Beach, & Chinsky, 1966; Locke & Fehr, 1970). It is therefore possible that children younger than 7 (and perhaps even older than 7 too) vary considerably in the extent to which they appreciate the benefit that rehearsal might bring, leading to variation in its use. Although one might link such behaviour to children's metamemory skills (Bebko, McMorris, Metcalfe, Ricciuti, & Goldstein, 2014; Schneider, 1985), it is also possible that the appropriate implementation of rehearsal requires top-down strategic control, at least among children (St Clair-Thompson, Stevens, Hunt, & Bolder, 2010) if not in adults (Dunlosky & Kane, 2007). This leaves open the possibility that children's strategic use of rehearsal reflects the executive aspect of working memory identified by Baddeley (1986).

6. Conclusions

Working memory performance is a strong predictor of real word abilities so there are clear educational benefits to be gained from a full and comprehensive understanding of its development. Both the Baddeley and Hitch (1974) and subsequent Baddeley (1986) models of working memory have been highly influential, and together they provide a sensible starting point for an examination of the developmental constraints on working memory performance in children. They capture three key phenomena: the fact that the maintenance of verbal and visuo-spatial representations can be dissociated to some extent, the possibility of additional domain-general constraints on working memory performance, and the potential importance of rehearsal. However, I have argued that a comprehensive account of working memory development in children, and of strengths and weaknesses in working memory performance among atypically developing individuals, needs to take into account additional factors, and to reconceptualise aspects of existing frameworks.

First, speed of processing is an additional constraint on performance, which relates to the ability to free up time for maintenance operations. Second, individuals also differ in their susceptibility to the detrimental effects of distraction, although this may not reflect any 'executive' ability to actively resist this distraction. Third, while rehearsal does provide a potential means of offsetting the forgetting caused by such distraction, I have argued that rehearsal is limited by an individual's ability to recall rather than being a causal determinant of their recall capacity. As a result, even young children should be able to rehearse a list that is within their recall capacity, but it is unclear whether these children lack the strategic, and potentially executive, abilities required to implement rehearsal effectively. This remains a question for further research, as is the extent to which rehearsal is limited to verbal material, and the related issue of whether domain-specific or domain-general processes support the ordered recall of verbal and visuo-spatial material.

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Author Note

Figure Captions

Figure 1. Illustration of the presentation phase of the verbal and spatial short-term memory tasks employed by Brock and Jarrold (2005). Participants then make their response by touching the appropriate locations on the touchscreen in the correct order.

Figure 2. Illustration of the presentation phase of one episode within a trial of any of the four complex span tasks employed by Bayliss et al. (2003) (a colour version is available in the electronic version of this paper). In tasks involving verbal processing the participant hears an object word (e.g., grass) and selects the target circle of the corresponding colour (green). In tasks involving visuo-spatial processing the participant selects the one target circle with a bevelled edge (represented here on the yellow circle with a shadow effect). They then remember either the digit within (verbal storage tasks) or the position of (visuo-spatial storage tasks) the target circle. The screen refreshes between each episode with new colours and digits in each position.

Figure 3. Illustration of the presentation phase of the forgetting task employed by Bayliss and Jarrold (2015) (a colour version is available in the electronic version of this paper). The participant hears a pre-load of three object words. They then carry out either 4 or 8 seconds of touching coloured targets on the basis of heard colour names (colour tasks) or by selecting the prototypical colour of heard object names (object task).
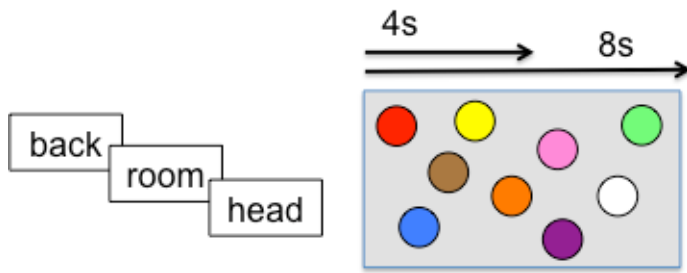
Verbal task
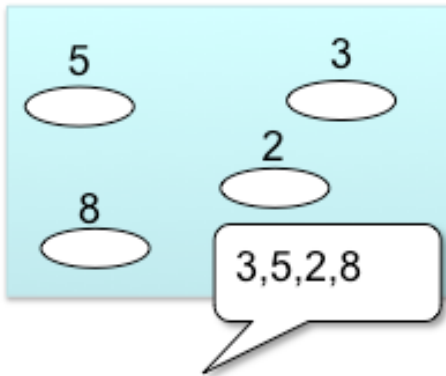
Spatial task
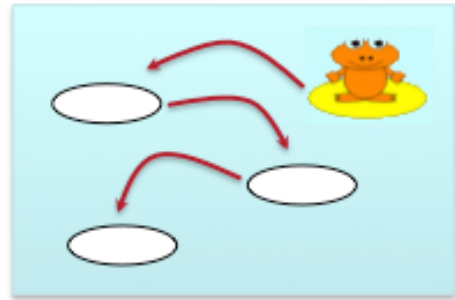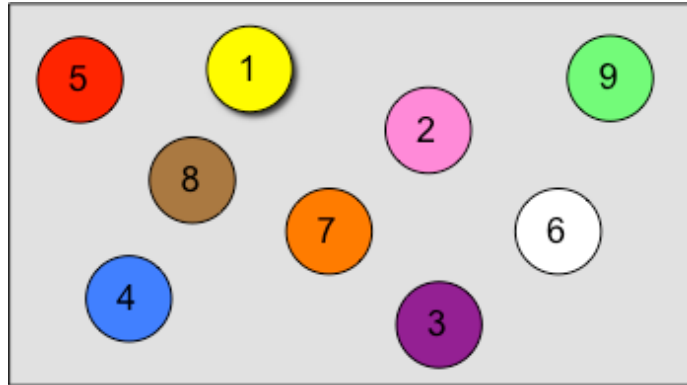
Colour task: "yellow", "green", …
Object task: "banana", "grass", …