Determinants of Auditory Selective Attention

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Declaration

I, Sandra Murphy, hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others, this is always clearly stated.

Signed: ________________________

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Abstract

Research into selective attention has for the last 50 years predominantly been focused on the visual domain (Driver, 2001). The aim of this thesis is to take established principles of visual selective attention and investigate whether they determine auditory distractor processing.

Firstly, the applicability of load theory in the auditory domain was considered (e.g. Lavie, 1995). Over five experiments, using two different perceptual load manipulations, I failed to find any evidence for a role of perceptual load within hearing. Two experiments investigating the influence of WM availability on processing of irrelevant singleton distractors further demonstrated that load theory does not seem to hold within the auditory domain.

Secondly, I investigated whether reported differences in everyday distractibility would relate to laboratory task-measures of auditory distractor processing. Over three experiments, I demonstrated some evidence of a relationship between a measure of everyday distractibility and task performance, such that participants reporting to be more distractible made more errors in the presence (vs. absence) of a singleton distractor sound compared with those reporting to be less distractible.

Lastly, I considered the role of monetary rewards on the ability to selectively focus on a target presented alongside a competing nontarget. The behavioural results suggested an influence of monetary reward, while the EEG measure failed to find any modulation.

Taken together, these results have contributed to further the understanding of attentional selection within hearing, and how it might differ from vision. For example, it seems that auditory distractor processing might be less open to modulations than visual distractor processing (at least in the context of load theory). However, levels of distractor processing might differ between individuals depending on how distractible they are in everyday life. Furthermore, a strong

motivation such as a monetary reward seems to have the ability to influence auditory attentional selection.

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Chapter 1 – General Introduction

Overview

In everyday life, vast numbers of different sounds reach our auditory system, some carrying more relevance to our current goals than others. Since the perceptual system does not have the capacity to process all sensory input at one time, selective attention plays the important role of focusing processing on relevant information at the expense of less relevant information. Whereas visual selection heavily relies on what information falls on the fovea in regards to what is perceived around us, there is no such equivalent in auditory attention. Instead, the ears are able to receive sound regardless of spatial origin and also in the dark. Thus, one might argue that there is an even greater need in audition than in vision to selectively attend to a portion of the input, as there are fewer inherent selection mechanisms in place. An abundance of research has demonstrated that this selective focus is indeed possible within audition (e.g. Cherry, 1953; Conway, Cowan, & Bunting, 2001; Hill & Miller, 2010; Wood & Cowan, 1995). However, other studies have demonstrated the inability to ignore irrelevant sounds, even when participants have been instructed to do so (e.g. Chan, Merrifield, & Spence, 2005; Moray, 1959).

This thesis will focus on a number of factors that are likely to determine the extent to which successful selection is possible and, as a consequence, whether or not distractor sounds are processed. In relation to the above-mentioned conflicting findings, the load theory (e.g. Lavie, 1995; Lavie, Hirst, De Fockert, & Viding, 2004) has attempted to provide a solution by the suggestion that successful selective attention is contingent upon the processing demands – or more specifically the perceptual load – that a relevant task requires. In addition, the availability of working memory (WM) capacity is argued to be central in order to maintain current task goals whilst ignoring irrelevant stimuli. Although Lavie and Tsal (1994) in a comprehensive review, which laid the empirical foundation for the role of perceptual load in focused visual attention, argued that the principles most likely would hold also in the auditory domain, the main focus and the evidence in support of the theory have predominantly derived from visual studies. As will become apparent later in this chapter, the small number of existing findings regarding the question of whether the same principles hold in hearing are mixed. For this reason, a large portion of the work presented in this thesis will specifically focus on investigating whether successful selective attention in the auditory domain also depends on the perceptual load in a relevant task, and on the availability of WM resources. The remainder of the work will then move beyond load theory to consider some other possible determinants of auditory selective attention, namely individual differences in everyday distractibility and the influence of monetary rewards.

This chapter will begin by providing a detailed account of perceptual load theory and the existing findings within vision and crossmodally (i.e. between vision and audition). A thorough review of the relevant auditory selective attention literature will then follow, taking into consideration studies that have investigated the role of perceptual load both directly and indirectly which, when taken together, will demonstrate the need for further research on this question. I will then review the existing literature on the role of WM load on distractor processing in both vision and hearing. I will move on to consider the importance of taking individual differences into account when measuring performance on selective attention tasks, focusing in particular on reported everyday distractibility and its potential links with the extent to which distractor processing occurs. I will proceed to discuss the effect of monetary rewards, which has been demonstrated to determine attentional selection in visual studies (e.g. Della Libera & Chelazzi, 2006). Lastly, I will present some methodological considerations which will inform the design of the experiments reported in the experimental chapters of this thesis.

Principles of Perceptual Load

A widely debated question in attention research has been whether selective attention operates at an early or late stage of processing. Early studies of auditory selective attention (which will be reviewed in further detail later on in this chapter) demonstrated conflicting evidence regarding whether unattended stimuli receive any processing at all. For example, Cherry (1953) demonstrated that when participants repeated back one of two simultaneous streams of sounds, one presented to each ear, very little was registered from the unattended stream. It was thus argued that attentional selection occurs early before full perceptual processing, meaning that only the selected stimuli receive such processing (Broadbent, 1958). Conversely, some studies showed evidence for processing of sounds in the unattended stream, such as participants noticing their own name (Moray, 1959). As a consequence, others, such as Deutsch and Deutsch (1963) claimed that all incoming stimuli are fully processed and that selection thus occurs at a much later stage. The theory of perceptual load (e.g. Lavie, 1995) offered a resolution to this longstanding debate, by arguing that selection can either occur early or late in processing, depending on the demands of the task at hand. The theory holds that perception has a limited capacity, which means that there is a restriction on how much information can be attended to in parallel. However, this capacity is automatically allocated until exhausted, which means that it is beyond volitional control in terms of how much capacity is used up. Instead, the level of perceptual load in a relevant task determines whether an irrelevant distractor is processed. If the task is perceptually easy (low perceptual load), any attentional capacity left will automatically be allocated to processing of surrounding, task-irrelevant stimuli. As a result, processing of the attended irrelevant stimuli will affect performance on the primary task, and selection will thus occur late. However, with a more perceptually demanding relevant task (high perceptual load), all the available capacity will be allocated to the task at hand and little irrelevant information will therefore be processed. Thus, attentional selection occurs early.

Operational Definitions of Perceptual Load

There are three main approaches most commonly represented in the literature regarding the characterisation of perceptual load. Firstly, the level of perceptual load is determined by the number of items in the relevant search display. For example, in a traditional flanker task (Eriksen & Eriksen, 1974), participants make responses regarding the identity of a target letter (e.g. X or N). The target is either presented on its own (low perceptual load) or amongst several other nontarget letters (high perceptual load; e.g. Lavie, 1995; Murphy, Van Velzen & De Fockert, 2012). Findings suggest that four or more items in a visual set display typically induce a high processing load (Lavie & Cox, 1997).

An alternative means of manipulating perceptual load is by varying the perceptual similarity between target and nontargets in the flanker task, while the number of items in the display remains constant (e.g. Forster & Lavie, 2008). For example, in a low load setting, a target letter (e.g. X or N) might be presented among o's which increases the saliency of the target and therefore little capacity is consumed in identifying it. In a high perceptual load setting, the nontarget letters would be of greater physical similarity to the target letter (i.e. angular letters such as H, K, M and W), placing a greater perceptual demand on identification of the target.

A third approach to define perceptual load is to keep the set display constant while changing the processing requirements of the relevant stimuli (e.g. Lavie, 1995; Rees, Frith, & Lavie, 1997), such as attending to one feature of the target (e.g. shape) for low perceptual load and a conjunction of features (e.g. shape and colour) for a high perceptual load setting (Treisman & Gelade, 1980). However, note that varying the processing demand levels may also lead to changes in other cognitive processes, such as executive functions. Thus, this way of characterising perceptual load could potentially be less reliable (Lavie & De Fockert, 2003; Tsal & Benoni, 2010).

Although the operational definitions of perceptual load are clearly characterised, it is nonetheless difficult to be precise in regards to the actual level of perceptual load in a given task. Attempts have previously been made to try and more directly quantify low and high perceptual load (e.g. Lavie & Cox, 1997), but in general reliance on such operational definitions runs the risk of creating a circular argument. More specifically, a failure to find reduced interference under high perceptual load could always be argued to be due to the perceptual demands not being high enough rather than providing a suggestion that the findings are not in line with the theory. Despite this, as the next sections will highlight, there is an abundance of evidence in favour of perceptual load theory which are based on the simple assumption that perceptual load has been successfully modulated if there is a significant difference in performance between high and low load (Lavie, 2010).

Evidence in Favour of Perceptual Load Theory in Vision

Behavioural Studies

In behavioural experiments, irrelevant distractor processing is often measured in terms of response competition. RTs in response to a target letter are compared as a function of the identity of an irrelevant distractor letter appearing in the periphery of the relevant set display. The distractor letter is either identical to the target letter (congruent distractor), identical to the other possible target letter, such that it corresponds with a button response opposite to that of the target (incongruent distractor), or of a different identity to both of the potential target letters (neutral distractor). This approach stems from the early work by Eriksen and Eriksen (1974), demonstrating slower RTs in the presence of a flanked incongruent (vs. congruent) distractor. Perceptual load theory predicts that the distractor interference measured through response competition — which is derived by comparing the RTs when a distractor is incongruent to the RTs when the distractor is neutral or congruent — is only evident in the low perceptual load condition, and this prediction has been firmly supported (e.g. Lavie, 1995; Lavie & Cox, 1997; Beck & Lavie, 2005). Thus, during trials where a high perceptual demand is imposed by the relevant task, it is argued that all available processing capacity is automatically allocated in order to perform the task. This consequently leads to little or no processing of the irrelevant distractor letter and therefore reduced interference is evident in the RTs.

Although the distractor letters in the typical response competition experiments are irrelevant to the task in a spatial sense, as they do not appear in the locations where a target may potentially emerge, they still carry some relevance through their characteristics in relation to the relevant stimuli as they are also letters and likely to be of the same identity as the targets (apart from a neutral distractor letter). Recently, the role of perceptual load on distractor processing has been extended to hold even when the distractors are completely irrelevant and highly salient (i.e. colourful cartoon characters) in comparison to the target and nontarget letters (Forster & Lavie, 2008). In addition, participants performed poorly in recognising meaningful objects previously presented as distractors alongside a flanker task in trials with a high perceptual demand compared with a low perceptual load condition (Lavie, Lin, Zokaei, & Thoma, 2009). Furthermore, the action a graspable distractor object (e.g. a mug or a saucepan) affords only influenced processing under low load (Murphy et al., 2012), while under high load the orientation of the handle did not interfere with hand of response. Altogether, these findings further support the notion of perceptual load determines whether processing of irrelevant stimuli occurs, even when the distractors are completely irrelevant to the task at hand.

The theory makes a clear distinction between the effects of perceptual load and the effects of general task difficulty, specifying that the key determinant of whether or not distractor processing occurs is the *perceptual* demands a specific setting requires. This was delineated in a study whereby various means of decreasing the target visibility – such as reducing size or contrast – resulted in increased task difficulty without any associated reduction in distractor interference (Lavie & De Fockert, 2003). These findings were linked to predictions regarding data limitations and resource limitations made by Norman and Bobrow (1975). They suggested that for data limitations, processing cannot be improved even when more perceptual resources are allocated to the task, which seemed to occur when target visibility was decreased. In contrast, resource limitations refer to tasks where there is a direct relationship between the applied resources and the success in task performance. Thus, the concept of resource limits closely corresponds with the notion of perceptual load, as allocating more perceptual resources to a perceptually demanding task improves performance. However, Yeshurun and Marciano (2013) noted that in Lavie and De Fockert's experiments, only the target had been manipulated in terms of discriminability, while the distractor was kept constant, which might have resulted in it being particularly salient in contrast with a degraded target. Therefore the distractor was also degraded to investigate whether it would still demonstrate the same level of interference, in line with Lavie and De Fockert's findings. Indeed, the level of interference persisted even with a degraded distractor. However, in contrast with the previous study which demonstrated even greater interference with a degraded target compared with a normal low load display, distractor processing was no different between the degraded and the normal display (Yeshurun & Marciano, 2013). These contrasting findings question the proposed distinction between sensory load and perceptual load made by Lavie and De Fockert. Furthermore, findings in line with this have also been reported by Benoni and Tsal (2012), demonstrating similar effects on distractor processing of both perceptual load and sensory load.

The measure of distractor processing through congruency effects may reflect fairly late response-level processing. For example, differences in distractor interference as a function of perceptual load could relate to post perceptual processes rather than an early influence determining whether the distractor receives any processing at all. However, the influence of perceptual load on conscious processing of irrelevant stimuli can be examined using a traditional inattentional blindness paradigm (e.g. Mack & Rock, 1998), measuring awareness of an unexpected, critical stimulus. For example, Cartwright-Finch and Lavie (2007) manipulated perceptual load on a task involving a cross with two arms of varying lengths. Under low perceptual load, participants made simple colour discriminations while under high perceptual load participants indicated which one of the two arms was longer. The unexpected stimulus consisting of a square appeared in the periphery in the final trial, along with the cross stimulus, and after responding to the cross participants were asked whether they had been aware of the unexpected stimulus. A higher occurrence of blindness to the unexpected stimulus was evident under high perceptual load, compared to the low perceptual load condition. These findings thus suggest for an early influence of perceptual load as conscious awareness changed as a function of perceptual demands. By contrast, in response competition paradigms, reductions in distractor interference under high load could be due to influences occurring at later stages in processing. However, the inattentional blindness paradigm may not necessarily reflect conscious perception, as a failure to report the occurrence of the unexpected stimulus may instead be due to a failure of memory rather than of perception (as argued by Macdonald & Lavie, 2008). For this reason, Macdonald and Lavie (2008) investigated the role of perceptual load in awareness by repeatedly presenting an irrelevant meaningless stimulus in the periphery, which was demonstrated to participants beforehand. Participants performed a letter identification task wherein perceptual load was traditionally manipulated by changing the similarity between target and nontargets under high and low load. Straight after each trial, participants made a response as to whether the irrelevant stimulus had been presented or not. Because potential memory decay was still a possibility even though participants were aware of the likely appearance of the irrelevant stimulus, one experiment also swapped the order of responses so that participants responded to the occurrence of the meaningless stimulus *before* making a response to the primary task. In line with the predictions of perceptual load theory, there was an increased rate of blindness in trials where the primary task was perceptually demanding (high perceptual load), even when attempting to reduce the possibility that the lack of awareness was due to a memory failure rather than a pure effect of perceptual load. Thus, these findings further imply that perceptual load determines the extent to which conscious perception of task-irrelevant stimuli occurs.

Neuroimaging Studies

Neuroimaging studies can provide a relatively direct measure of distractor processing, without the need for an explicit behavioural response. This is particularly important in light of the potential confounds associated with the behavioural paradigms described in the previous section. For example, in an fMRI study activity in relation to processing of an irrelevant visual motion (vs. static) stimulus (presented in the periphery of the display) was measured while participants performed a visual task consisting of single words presented centrally

(Rees et al., 1997). Under low load, participants made a response whenever the word was presented in capital letters, while under high load a response was prompted for words consisting of two syllables. Thus, the stimuli remained constant over the two perceptual load manipulations, while the processing demand of the stimuli differed between the two tasks. Activity in area V5 (involved in visual motion processing) differed as a function of load, with a significantly weaker activity under high (vs. low load) in the presence of the motion (vs. static) distractor. This finding clearly suggests that perception of the irrelevant motion distractor was determined by the level of perceptual load in the relevant task, providing important converging evidence with the behavioural research described earlier.

While many studies have used relatively neutral distractors such as moving (vs. static) dots (e.g. Rees et al., 1997), other findings have suggested that perceptual load can also determine the processing of highly emotional stimuli such as fearful faces. Bishop, Jenkins and Lawrence (2007) used a visual search task – where perceptual load was manipulated by contrasting the similarity between target and nontargets – which was superimposed on a face with either a fearful or neutral expression. fMRI data demonstrated increased activity in the amygdala when exposed to a fearful face compared to a neutral face. However, this surge in activity was only evident when the relevant task was of low perceptual load. Furthermore, differences in amygdalal activity between individuals with low vs. high levels of anxiousness were seen in the low perceptual load condition, whereas under high perceptual load the response of the amygdala was equal. Thus, an increase in perceptual demands of the relevant task reduced processing of the irrelevant face to such an extent that individual differences in anxiety levels no longer were evident. Findings such as this closely link to the typical behavioural patterns demonstrated and consequently provide further support for the role of perceptual load in whether distractor processing occurs.

Apart from the advantage of not requiring a behavioural response to measure distractor processing, neuroimaging also has the ability to more closely investigate how early in perceptual processing the influence of perceptual load can occur (although note that the temporal resolution of the fMRI technique is generally quite poor). Recently, fMRI studies have demonstrated early modulations of perceptual load in areas which may occur before reaching awareness. For example, Bahrami, Lavie and Rees (2007) presented participants with a central stream of letters. Under low load, responses were made to a specific letter identity regardless of letter colour, while under high load participants focused on a conjunction of colour and letter identity. In the periphery, a faint drawing of an object was simultaneously presented to one eye, which was made invisible through the concurrent presentation of salient flashing masks to the other eye. The activity in area V1 that was associated with the appearance of the invisible object (compared with its absence) was reduced as perceptual load increased, which suggests that the perceptual demands of the relevant task can even determine unconscious processing at very early stages of visual input. Similarly, adaptation to orientation of invisible gratings of irrelevant objects presented in the periphery (using the same flash suppression technique as in Bahrami et al. (2007) was only seen under low perceptual load while there was no evidence of such adaptation under high load (Bahrami, Carmel, Walsh, Rees, & Lavie, 2008). In line with these findings, a previous study demonstrated even earlier modulations of perceptual load in the visual domain (O’Connor, Fukui, Pinsk, & Kastner, 2002). Similarly to Bahrami et al. (2007), participants focused on a central stream of letters while ignoring a flickering checkerboard pattern presented to the left or the right hemifield. Under low load, participants simply counted the infrequent colour change of an appearing fixation cross, whereas under high load they counted all the letters presented in the stream. A reduction in activity in response to the checkerboards was not only seen in the visual cortical areas such as V1 under high (vs. low) load, but there was also reduced neural processing evident in the lateral geniculate nucleus (LGN): an area which receives retinal input before it is subsequently projected into the visual cortex. This finding therefore further suggests that attentional modulation can occur as early as in subcortical regions of the visual system, and furthermore it is the perceptual demands of the relevant task that determines the strength of which unattended irrelevant stimuli are processed at this stage.

It is nearly 20 years since the perceptual load theory was coined (Lavie & Tsal, 1994; Lavie, 1995), and over this period the evidence in favour of perceptual load has been wide ranging, as highlighted in the past two sections (although since the focus of the thesis is on the auditory domain only a subset of all the findings has been reviewed). Thus, the theory remains very influential, and recently the role of perceptual load has for example begun to be investigated in clinical populations such as individuals with autism (e.g. Remington, Swettenham, & Lavie, 2012) and ADHD (Forster, Robertson, Jennings, Asherson, & Lavie, 2013; as cited in Forster & Lavie, 2013). Whether such a strong and robust influence holds in hearing is yet to be established.

Crossmodal Studies

Although the role of perceptual load has been widely established within vision, these findings do not provide information concerning whether the same principles would hold in hearing which is the focus of the current thesis. However, there has been a small amount of audiovisual research on this topic. In Rees, Frith and Lavie's (2001) fMRI study, participants either made discriminations of the loudness of spoken words (low perceptual load) or counted the number of syllables they contained (high perceptual load), whilst ignoring a visual stimulus consisting of white dots which were either moving or static. There was no difference in distractor-related activity in area V5 between the two perceptual load conditions, suggesting that the task-irrelevant motion distractor was processed to the same extent under both high and low auditory perceptual load. Similarly, Tellinghuisen and Nowak (2003) adapted a conventional visual perceptual load paradigm to investigate crossmodal perceptual load, but they addressed the influence of auditory distractors (rather than targets). When standard visual distractors were used, processing was only evident in the low load condition — as predicted by load theory. However, auditory distractors were processed across both load conditions, bringing into further question the role of perceptual load in crossmodal contexts. These findings might thus suggest that capacity limitations within selective attention are modality specific rather than encompassing several sensory modalities (although note that this suggestion would still imply that perceptual load theory should hold within audition).

However, in contrast to these early findings, a few recent studies have indeed found an effect of perceptual load across modalities, questioning the suggestion that processing capacity is modality-specific. For example, Klemen, Büchel and Rose (2009) presented participants with a sequence of tones, and the task was to indicate whether the present tone matched the previously presented tone. Perceptual demands were manipulated in the similarity in pitch between the presented tones, resulting in a more difficult discrimination task under high (vs. low) load. Concurrently, images of different levels of visibility were displayed on screen. It was demonstrated that during the difficult auditory discrimination task, activity in the lateral occipital cortex (reflecting processing of the images) was less activated than under low load, which suggests that the demands of the auditory stimuli affected processing of the visual irrelevant stimuli, which is in line with the predictions of load theory. However, the load manipulation, which involved keeping a memory trace of the previously presented sound in order to match it with the following sound, seems likely to have reflected differences in auditory short-term memory demands rather than perceptual demands. Indeed, a recent unimodal study has demonstrated that loading visual short-term memory leads to a reduction in processing of irrelevant visual distractors (Konstantinou, Bahrami, Rees & Lavie, 2012). Thus, the predictions of load theory are similar for short-term sensory memory load as they are for perceptual load, despite the demands involving different mechanisms of sensory processing. It is therefore likely that the findings of Klemen et al. reflect the influence of auditory short-term memory rather than auditory perceptual load on visual processing.

Nevertheless, one recent study did not suffer from the potential confound of manipulating short-term memory load rather than perceptual load. Macdonald and Lavie (2011) investigated the effect of visual perceptual load through awareness report of an auditory critical stimulus, using a visual discrimination task similar to the task used by Cartwright-Finch and Lavie (2007) and mentioned earlier. Similarly, participants made a simple colour judgement under low load, whereas under high load they judged which of the two arms of the cross was longer. Simultaneously, white noise was played over headphones during each trial. On the final trial, a critical tone was briefly embedded in the white noise channel, and participants were directly asked upon making the task response whether they had been aware of its presence. There was a significant increase in inattentional deafness to the tone under high (vs. low) visual perceptual load, and this finding remained even when the continuous white noise presented in the other trials in Experiment 1 was omitted (Experiment 2) which created a higher signal to noise ratio for the appearance of the critical stimulus. Therefore, the results suggest that the level of perceptual load in a visual setting might be a determinant of inattentional deafness. In line with Macdonald and Lavie, an earlier study investigating the effect of visual load on auditory distractor processing also found some modulations as a function of task demands (Otten, Alain, & Picton, 2000). Participants were monitoring a rapid visual sequence of digits, and either reported the value (smaller or larger than 5) of the previous digit (high load) or the present digit (low load) which was determined by the colour of the present digit. Sounds were concurrently presented at either a slow or rapid presentation rate, and occasionally a deviant sound occurred. ERPs in relation to the deviant sounds were measured as a function of task demand. Although processing of the deviant sound did not seem to change as a function of load, there was a reduction in amplitude around the right temporal electrode site under high load (around 200 ms) and a later (around 450 ms) negative wave in frontocentral locations for rapidly presented tones which was only seen under low load. Thus, it seems that there may have been some differences in processing of the deviant sound as a function of visual load. However, the actual functions of these differences remained fairly undeveloped. Furthermore, it is worth noting that a 0-back (low load) vs. a 1-back (high load) manipulation might reflect a manipulation of WM load rather than perceptual load, which makes the findings harder to reconcile.

In addition, there are a number of crossmodal studies which have investigated the influence of auditory/visual perceptual load on the use of auditory and/or visual peripheral cues (e.g. Santangelo, Olivetti Belardinelli & Spence, 2007; Santangelo & Spence, 2007). For example, one study demonstrated effects of crossmodal perceptual load through a reduction in peripheral visual cueing effects under high auditory load compared with low auditory load (Santangelo et al., 2007). Under high load, participants responded to or simply focused on a central stream of sounds, while under low load the cueing task was performed on its own. There was a reduction in cueing effects observed under high (vs. low) load, which suggests that focusing on the central stream exhausted processing capacity, resulting in a reduction in processing of the cues. The same results were also demonstrated in a setting whereby the task was visual and auditory peripheral cues were presented. However, the two high load conditions involved an additional auditory or visual stream compared with the low load condition. This addition is likely to have changed perceptual factors other than perceptual load, such as the focus of spatial attention and perceptual grouping. It is thus possible that the reduction in peripheral cueing seen under high load might have related to these changes.

The findings reviewed above clearly demonstrate that there is not yet a consensus as to whether perceptual load holds across sensory modalities. However, the inconsistency in findings might be due to the modality in which perceptual load was manipulated. While Rees et al. (2001) found no modulation of visual distractor processing as a function of auditory perceptual load, Macdonald and Lavie (2011) and Otten et al. (2000) found evidence of a crossmodal modulation of auditory distractor processing by visual perceptual load. It might thus be that processing of distractors from a different modality can only be reduced when the primary task is visual, while increased perceptual demands in an auditory task will not affect visual distractor processing. However, the failure to find a modulation reported by Tellinghuisen and Nowak (2003) contradicts this suggestion. Nevertheless, regardless of the mixed findings, none of the crossmodal studies relates directly to the question of whether perceptual load holds in hearing because none of them included a purely auditory condition.

So far, I have outlined the principles of perceptual load theory and provided an extensive review of both visual and crossmodal findings. I will now begin reviewing the literature on auditory selective attention which is indirectly relevant to the question of whether perceptual load holds in hearing before moving on to a number of studies providing more direct investigations.

Dichotic Listening Tasks and the Locus of Attentional Selection

Research on auditory selective attention was largely initiated by some seminal work by Cherry (1953). Although conducted nearly sixty years ago, the fundamentals of his experiments are still widely used – albeit with a more robust and sophisticated methodology. In a classic shadowing task, participants are asked to repeat aloud one of two different streams of speech sounds presented simultaneously, one to each ear (i.e. dichotically). One of the central questions in such tasks is how much of the unattended message participants perceive. A common finding is that – when questioned after the shadowing task – participants have very little knowledge of the content of the unattended channel, and they are often prone to missing important events such as a change to a different language (Cherry, 1953), the speech being played backwards (Wood & Cowan, 1995), or even the same word being repeated several times (Moray, 1959). However, when the gender of the talker is changed or the speech replaced with a pure tone, detection is highly likely (Cherry, 1953).

In relation to the dichotic listening tasks, Broadbent (1958) noted that although two talkers in some cases can be attended to at the same time, this ability is strongly contingent upon the amount of information that is being presented within these streams. Thus, he formed the filter theory, which holds that there is a great restriction in the amount of information that can be attended to concurrently. When stimuli are presented simultaneously, only the physical properties such as frequency and intensity (when referring to sounds) will be processed for all stimuli, and this forms the foundation from which a limited amount of information is selected through a filter for further processing which subsequently will reach awareness. The rest of the irrelevant information will instead be briefly held in memory, after which it is most likely to decay. According to Broadbent, this filtering process could explain the findings of studies such as Cherry's (1953), where only rudimentary features but no semantic contents were reported from the unattended channel in a dichotic listening task. He thus concluded that attentional selection occurred early on in perceptual processing, which furthermore implies that stimuli cannot be fully processed in parallel due to the capacity limit within the perceptual system.

Contrary to Broadbent’s filter theory, Moray (1959) demonstrated that some participants in a dichotic listening task were able to notice their own names being presented in the unattended stream. This suggests that the message in the unattended ear must have been processed to a semantic level rather than simply the physical features, which contradicts Broadbent’s suggestion that all available stimuli cannot be fully processed in parallel. Similarly, Treisman (1960) demonstrated that when the content of the two messages in a dichotic listening task suddenly changed over between the two ears, a substantial number of participants would start repeating from the unattended channel which now contained the narrative they were reiterating from the attended ear. Furthermore, Lewis (1970) measured the level of processing of the words in the unattended message of a dichotic listening task through examining RTs to repeated words in the attended message as a function of whether the words in the unattended channel were related or unrelated to the target words. Although participants were not able to recall the content of the unattended stream, words that were of semantic relation to the repeated words produced interference, which was evident through slower RTs compared to the unrelated words. Taken together, these findings imply that even the content of the irrelevant message was processed to an extent beyond possibility within the framework of Broadbent’s theory. Contradictive results as the above in relation to Broadbent’s theory made others (e.g. Deutsch & Deutsch, 1963) argue that attentional selection does not operate at an early stage in perceptual processing, but rather at a later stage, namely, the level of response selection. Thus, they suggested a perceptual system whereby stimuli are fully processed in parallel.

However, the studies in support of a late selection account (e.g. Lewis, 1970; Moray, 1959;. Treisman, 1960) may not have controlled for whether momentary shifts of attention occurred which consequently led to processing of the task-irrelevant material. Lachter, Forster and Ruthruff (2004) investigated this possibility using a strict measure of attentional focus. As this was the main priority of the study, they used a visual task to more accurately monitor potential attentional shifts. A prime word was presented either in a location which was likely to be either attended or unattended (for example, due to cueing of the prime location) prior to the task display, which consisted of a string of letters. The task was to determine whether the letters formed a word or not, and it was found that responses were faster when the prime and the target were of the same identity. However, this priming effect was only seen when the prime appeared in attended locations. Overall, these findings demonstrated that in order for stimuli to be fully processed, they have to be attended to in the first place, which largely corresponds with Broadbent's ideas.

The dichotic listening experiments are important as they demonstrate situations whereby very little information from the unattended stream seemed to have been processed. This could arguably relate to the high perceptual demands of the relevant task, which involved participants not only attending to the relevant stream but also encoding each auditory object in order to repeat back the message. Thus, the lack of processing in the unattended channel under such condition could be in line with perceptual load theory. However, the experiments did not include manipulations of perceptual demands of the relevant tasks, which make it difficult to draw any conclusions about the role of perceptual load in these findings.

EEG Studies of Auditory Selective Attention

Apart from the early behavioural dichotic listening studies, much of the research addressing the influence of selective attention on perceptual processing has been conducted through EEG studies. Most experiments involve tasks of detection or discrimination to simple target tones which differ from other tones on a physical feature such as intensity, frequency or duration. The amplitude of the ERP waveforms is compared when stimuli are attended versus when they are unattended. A range of studies have offered support for the early selection view, such that focusing of attention has resulted in increased sensory processing as early as 60 ms after stimulus presentation (e.g. Hansen & Hillyard, 1980; Woldorff & Hillyard, 1991; Woldorff et al., 1993). For example, Woldorff and Hillyard (1991) presented rapid sequences of tones of different frequency to either ear. The task involved focusing on the sequence in one ear and responding to infrequent target tones differing in intensity from the other tones in the stream, while ignoring the stream presented to the other ear. Thus, the experimental design was similar to the dichotic listening task with the exception of using less complex sounds than speech. There was an early increase in ERPs (20–50 ms after stimulus onset) to the attended stream compared to the unattended stream, strongly supporting early selection and narrowing of attention for enhanced processing of relevant stimuli. However, as perceptual demands were not specifically manipulated in this task, it is again hard to determine whether perceptual load played a role in the early selection evidence.

Mismatch Negativity (MMN)

A large number of EEG studies have investigated the role of selective attention through investigations of the mismatch negativity (MMN). The MMN is a negative waveform elicited in the presence of an ‘oddball’ sound which differs from a uniform sequence of auditory objects. A widely investigated question in the MMN literature is whether detections of deviants as measured through the MMN is open to attentional modulation, which has been widely debated as some studies have suggested that deviance detection can occur even in the absence of attention (e.g.

Näätänen, Paavilainen, Rinne, & Alho, 2007). For example, it has been demonstrated that the MMN in response to deviant tones was of the same amplitude regardless of whether the deviants were presented in the attended or the unattended channel (Alho, Woods & Algazi, 1994). However, other studies have demonstrated a reduced MMN when attention is focused elsewhere (e.g. Alain & Woods, 1997; Müller-Gass, Stelmack & Campbell, 2005; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993; Trejo, Ryan-Jones, & Kramer, 1995). For example, Trejo et al. (1995) presented participants with two central streams of sounds, one containing a sequence of tones and one containing a spoken message. The task was either to attend to the narrative and make a response whenever a specific word appeared, or to attend to the tones and respond to a frequency deviant. There was also a different frequency deviant, which the MMN was measured in relation to. It was demonstrated that the MMN was decreased whenever participants attended to the message, compared with the sequence of tones. This suggests that attention modulates the extent to which the MMN is elicited in the presence of a deviant sound. In line with this claim, Alain and Woods (1997) reported similar findings but this time in relation to MMN in response to a pattern deviant. Participants were presented with tones of high or low frequency, one to each ear. Within each ear, the tones also alternated in frequency, with the occasional repetition of a tone which resulted in a deviation from the pattern. In the attend condition, participants made responses to the deviants in the attended ear whilst ignoring the unattended deviants, and in the passive condition participants read a book whilst being presented with the sounds. The MMN response to the pattern deviant was significantly reduced in the unattended ear and during reading, compared with the attended ear which suggests for a modulation of attention on the extent to which a deviant is processed.

Overall, it seems that the MMN is only modulated by attentional allocation under certain conditions, for example when the target is highly similar to a deviant in the unattended stream (e.g. see Sussman, 2007, for review). However, similarly to the behavioural dichotic listening studies (e.g. Cherry, 1953), these early EEG studies and the MMN investigations described so far did not manipulate the perceptual demands of the relevant task, making it hard to draw any conclusions in terms of whether perceptual load theory holds in hearing.

ISI Manipulations of Perceptual Demands

However, other EEG studies have included direct manipulations of task demands, such as variations in interstimulus interval (ISI). Parasuraman (1980) measured the amplitude of the N1 (an early negative waveform susceptible to attentional modulations) that was elicited by both attended and unattended stimuli (separated by ear). The N1 waveform differed depending on how difficult the target was to discern from the nontargets in a sequence, and also depending on the rate at which the stimuli were presented. More specifically, the N1 elicited by the attended stream was greatest compared to the N1 elicited by the unattended stream when the target was hard to distinguish and when the sequence was presented at a high speed. A low presentation rate on the other hand resulted in a remarkably smaller difference in amplitude between attended and unattended stimuli, which suggests that both streams were perceived in this instance. The results are in line with the principles of perceptual load theory as they imply that the locus of selective attention is strongly contingent upon the specific processing demands of the relevant task.

Similarly, Woldorff, Hackley and Hillyard (1991) found an effect of processing of stimuli in the unattended stream as a function of ISI. Using a similar task to Woldorff and Hillyard (1991) whereby two different streams were presented (one to each ear), the MMN elicited to deviant sounds in the attended and in the unattended stream was measured. The results demonstrated decreased amplitude of the MMN elicited by deviant sounds in the unattended channel, compared to the MMN in response to those in the attended channel. Furthermore, when the ISI in a second experiment was increased to create a more demanding task, there was no significant MMN activity in the presence of a deviant sound in the unattended channel, while in the attended channel an elicited MMN was still seen. This therefore suggests that the occurrence of MMN is modulated by attention and furthermore that this is determined by the demands of the relevant task. Again, this suggests for a potential role of perceptual load also in hearing.

In addition, a more recent ERP study (Neelon, Williams, & Garell, 2011) used intracranical recordings (ECoG) rather than EEG. While EEG is noninvasive, ECoG is recorded directly on the cerebral cortex. Thus, ECoG is advantageous as it provides a better spatial resolution and overall a clearer recording of signals than EEG. Perceptual load was similarly manipulated through ISI, and the task involved making responses whenever a deviant tone appeared in the relevant stream. It was found that for slower ISIs, there was an enhancement in grand-average ERP waveforms related to processing of both the attended and the unattended channel. Conversely, only the ERPs in response to the relevant auditory stream were enhanced during faster ISIs, implying that the irrelevant stream was not processed to the same extent. The results therefore support the notion that the level of perceptual load determines whether irrelevant auditory stimuli are processed. However, one caveat is the fact that the study was conducted on epileptic surgery patients. Although careful restrictions were utilized to ensure the clinical population would be as similar as possible to a normal population, the results have to be interpreted with caution and therefore can only provide preliminary evidence in favour of the perceptual load theory in audition. It is also important to note that although the behavioural results suggested (through numerical trends) that the task became more demanding as ISI rates got faster, performance was not significantly different between the conditions. This adds further reason to question whether the results reliably demonstrated that the principles of perceptual load theory also could be applied to an auditory setting.

Taken together, the studies reported so far using ISI to manipulate perceptual demands suggest that faster presentation of attended stimuli leads to reductions in processing of unattended stimuli, as measured by a range of different ERP components. This suggests that the locus of auditory attention is contingent upon the specific processing demands of the relevant task, providing initial support for the applicability of perceptual load theory in hearing.

However, not all studies manipulating ISI have found reduced processing in the unattended channel with increase in presentation speed. For example, Gomes, Barrett, Duff, Barnhardt, and Ritter (2008) manipulated ISI in a paradigm whereby participants were presented with two auditory channels, and attended to one based on frequency of the sounds, whilst ignoring the other. The task involved making a button response whenever a tone of lower intensity than standard appeared in the attended channel. The Nd magnitude was utilised to measure the difference between performance in a fast ISI (high perceptual load) task and performance in a slower ISI (low perceptual load) task. The Nd component is the negative difference between ERP waveforms when presented stimuli are attended from when they are unattended. Perceptual load theory would predict a larger Nd wave in the fast ISI condition as a result of less distraction from the irrelevant channel. However, although accuracy was lower in the fast ISI condition, the Nd wave was unaffected by the ISI manipulation. The authors thus concluded that successful selective attention is not modulated by perceptual load in the auditory domain, which stands in clear contrast to the findings by Neelon et al. (2011), Parasuraman (1980) and Woldorff et al. (1991).

In addition, earlier work on auditory scene analysis (e.g. Bregman, 1990) has indicated that presenting sounds with smaller temporal separation can strengthen the processes of perceptual segregation in the auditory scene (as argued, for example, by Francis, 2010). This means that manipulations of ISI are potentially confounded by concurrent changes in the strength of perceptual segregation between high and low load, making it difficult to draw conclusions regarding the potential role of perceptual load in hearing based on this type of manipulation.

Direct Measures of Perceptual Load Using MMN

However, one EEG study did not suffer from this confound as ISI was kept constant for both perceptual load conditions. Instead, Alain and Izenberg (2003) used a feature versus conjunction task to manipulate perceptual demands. Participants were presented with two streams of sounds, one to each ear. Both streams included tuned and mistuned stimuli, and participants were informed which ear to attend to. Under low load, the task involved detecting infrequent targets defined by short duration, while under high load participants were also asked to report the tuning (tuned vs. mistuned) of these short duration targets. MMN elicited in the presence of short duration deviant stimuli in the unattended ear was decreased when participants performed the conjunction task (high load) compared with the MMN elicited during the feature task (low load), which was in line with the predictions of perceptual load theory.

However, the two tasks used by Alain and Izenberg (2003) are likely to have resulted in differences in ‘attentional set’. While the high load task which required attention to both duration and tuning would have resulted in participants implementing an attentional set including both dimensions, the low load task only emphasised duration. Thus, duration (the defining feature of the deviant as well as the target) is likely to have been more strongly prioritised under low load than under high load. Thus the reduction in MMN amplitude in response to a duration deviant in the unattended channel under high (vs. low) load could be related to the reduced priority of duration in the high (vs. low) load task, rather than to differences in the availability of processing capacity. In fact, there is substantial evidence that the attentional set required for the task is important in determining the extent to which task-irrelevant deviants capture attention, both in vision (Bacon & Egeth, 1994; Folk, Remington & Johnston, 1992) and in hearing (Dalton & Lavie, 2007). Therefore, these results cannot be taken as clear support for the applicability of load theory to hearing. Indeed, a more recent task, which is unlikely to have involved changes in the focusing of participants’ attentional set between conditions, failed to demonstrate any differences in MMN amplitude as a function of task demands (Müller-Gass & Schröger, 2007). Participants made judgements to the duration of tones presented binaurally, and task demands were manipulated through the difference in duration between the short and the long tones. Despite the fact that the attentional set between high and low load would have been the same, as both conditions required duration judgements, the amplitude of the MMN elicited by occasional low frequency deviants did not vary across load conditions.

The problem related to changes in attentional set between high and low perceptual load only applies when the stimuli in the attended and unattended streams are highly similar. By contrast, a recent MEG study (Chait, Ruff, Griffiths & McAlpine, 2011) presented participants simultaneously with a sequence of auditory ‘objects’ (a mixture of pure tones, frequency-modulated tones, glides and white noise) to one ear, a sequence of brief tone ‘pips’ in the other ear, and a sequence of visual ‘objects’ (different shapes such as a triangles, circles and squares) on the screen. The task was either to attend to the auditory or visual objects while ignoring the stream of ‘pips’. At the start of each trial, participants were presented with the target shape (which was one of the different objects) and the task was to detect the occurrence of the target in the attended sequence. Under low load, the target was always the same, while under high load the target identity changed every trial. While the visual task load had no effect on change detection in the unattended stream, increased auditory load resulted in less cortical activity in response to a change, but only when these changes constituted an irregular pattern becoming regular (rather than a regular pattern becoming irregular). However, perceptual load theory was not the focus of the study, and indeed the load manipulation involved increased memory demands under high (vs. low) load rather than perceptual demands. This makes it hard to interpret these findings in relation to whether perceptual load applies within audition.

Behavioural Investigations of Auditory Perceptual Load

The EEG studies that have directly investigated the effect of perceptual load in hearing not only report mixed findings, but also suffer from a range of confounds which makes it all the more difficult to draw any conclusions based on them alone. However, a number of behavioural studies that do not suffer from these confounds have also examined the role of perceptual load in hearing. For example, Santangelo and Spence (2009) described an unpublished study by Chan and Spence, whereby a task similar to Rees et al. (2001) was used involving the presentation of sequences of spoken words over speakers. The words consisted of one to three syllables, and each word was presented either with high or low intensity. Under low load, responses were made to the intensity of each stimulus while under high load participants judged whether or not the word consisted of two syllables. Distractor processing was measured using auditory motion after-effect (MAE; e.g. Grantham & Wightman, 1979). This typically occurs after repeated exposure to sounds moving in one direction, whereby a subsequent presentation of a stationary sound is then perceived to be moving in the opposite direction. The MAE was induced by a concurrent sound presented over headphones, which swept from one headphone to the other. Following this, a sound appeared at the centre in respect to the head, and participants judged whether the sound had seemed to be moving to the left or to the right (i.e. the same or opposite direction from the sweeping sound). In line with the predictions of perceptual load theory, the frequency of the auditory MAE (i.e. reports of the opposite direction in relation to the sweep) was decreased as load increased. Thus, it seemed that the distractor sound was processed to a lesser extent compared with performance under low load. However, there might be other possible explanations for the reduction under high load compared with low load than a pure modulation of perceptual load. For example, target responses under low load would have resulted in shorter reaction times, making it possible for participants to switch their attention to the sweeping sounds more readily than under high perceptual load. This in turn might have altered the extent to which the auditory MAE occurred. However, since the study was only briefly described, it is difficult to be precise about such possibilities.

However, another study also demonstrated effects of auditory perceptual load, this time through a reduction in peripheral auditory cueing effects under high load compared with low load (Santangelo et al., 2007). This experiment used an identical task to the previously mentioned crossmodal experiments, whereby participants responded to or simply focused on a central stream of sounds (high load), which was compared with performance of the auditory cueing task on its own (low load). The significant reductions in cueing effects observed under high load led Santangelo et al. to conclude that focusing on the central stream exhausted processing capacity, resulting in significantly less processing of the auditory cues, which is in line with the predictions of perceptual load theory. However, similarly to the previously mentioned crossmodal study, the inclusion of an additional auditory stream under high versus low load is likely to have also altered other perceptual factors than perceptual load alone. It is therefore likely that the results are related to such changes, making these findings hard to reconcile.

However, a more recent behavioural study investigated auditory perceptual load without the potential confound of changing perceptual factors other than perceptual load. Francis (2010) used an adapted auditory version of the traditional visual flanker task (Chan et al., 2005) to examine the effect of perceptual load on speech perception. Participants were presented with two streams of spoken words, either ‘bead’ or ‘bad’. The primary task was to indicate which of the two words had been presented in the relevant stream whilst ignoring the irrelevant. The perceptual load manipulation, incorporated into a secondary task, was a tone altered in terms of pitch (high or low) and amplitude modulation (either modulated or not). In the low perceptual load condition, participants only attended to one of the two altering features, and to a conjunction of the features in the high perceptual load condition. Responses regarding the identity of the spoken words were only supposed to be provided when the tone followed a specific prerequisite. The relevant auditory stream was either determined by location (i.e. attend to the stream appearing from the centre whilst ignoring the stream appearing from the periphery) or by gender (in which case both sounds appeared from the same, central location). Regardless of the means by which attention was directed, it was found that high perceptual load led to reduced interference from the irrelevant distractor words, which was evident through smaller congruency effects in comparison to performance under low perceptual load. Thus, Francis concluded that perceptual load seems to play a central role in speech perception, as the results suggest that it determines the extent to which response competition occurs due to the inability to ignore irrelevant speech. Although this study provides preliminary support for the role of perceptual load in audition, it is worth noting that the load by congruency interaction which is the typical indication of a role of perceptual load was not significant (F < 1 in both experiments). Instead, Francis compared the mean difference in RT between congruent and incongruent trials for high and low perceptual load, and found that the low load condition showed a significantly larger interference effect than did high load. Thus, the lack of a significant interaction questions the strength of these results.

The reviewed literature on the existing studies investigating auditory perceptual load reveals a mixed pattern of findings. The studies providing direct support for perceptual load theory (e.g. Alain & Izenberg, 2003; Francis, 2010; Santangelo et al., 2007) all have confounding aspects, making it difficult to draw any firm conclusions based on these findings alone. Conversely, there is also evidence suggesting that perceptual load does not hold in hearing (e.g. Gomes et al., 2008). However, these findings are also not entirely reliable due to the nature of the load manipulation used. Thus, it remains clear that a more thorough investigation into whether perceptual load holds in hearing is warranted. This will be the aim of Chapters 2 and 3 of this thesis.

The Role of Working Memory (WM) Load

Following an initial focus on perceptual load, the theory was next expanded (De Fockert, Rees, Frith, & Lavie, 2001; Lavie et al., 2004) to address the role of executive functions such as working memory (WM) in selective attention. It is argued that the availability of WM load capacity is of importance in maintaining current task priorities. Contrary to the effects of perceptual load, it is predicted that an increase in WM load should result in an increase of distractor processing due to the reduced ability to remain task-focused. The first direct investigation into the effect of WM load on focusing of attention involved a neuroimaging study (De Fockert et al., 2001), whereby participants were presented with faces (famous or anonymous) with a famous name superimposed. The task was to determine whether the name belonged to a pop star or to a politician whilst ignoring the distractor face which was congruent, incongruent or neutral in respect to the name.

During the selective attention task, participants rehearsed a string of five digits which were presented at the very start of the trial (i.e. before the attention task stimuli) either in a sequential ascending order (low WM load) or a random order (high WM load). Following the selective attention task, a probe appeared and participants indicated what digit had followed the one presented on the screen (in order to confirm that the memory set had been held in mind effectively throughout the trial). More interference from the irrelevant distractor was evident under high WM load (vs. low WM load), along with increased activity as measured by fMRI in the brain areas related to processing of the faces. Furthermore, a high WM load task was linked with increased activity in the prefrontal cortex, confirming the increase in executive functions. Thus, this study demonstrates the critical role of WM load in the extent to which perceived irrelevant distractors have a detrimental effect on task performance.

There is also evidence for the role of WM load on distractor processing from behavioural measures. For example, Lavie et al. (2004) employed a visual flanker task and measured distractor interference as a function of the demands of a concurrent WM task. Similarly to De Fockert et al. (2001), participants were presented with either one digit (low WM load) or six digits in a random order (high WM load) prior to the selective attention task. Following the flanker task the memory probe digit appeared, and participants indicated whether or not the digit had been part of the previous sequence. In line with De Fockert et al. (2001) an increase in distractor interference under high (vs. low) WM load implied that the reduction in available WM capacity left participants more susceptible to distraction (presumably because they were less able to maintain current task priorities). Thus, this provided further evidence for the critical role of WM load in determining the extent to which irrelevant distractors interferes with task focus.

The importance of available WM capacity in the ability to stay focused on the relevant task has also been extended to a range of other task set-ups. For example, De Fockert, Mizon, and D’Ubaldo (2010) found that performance on a negative priming task was dependent on the level of WM load in a concurrent task. For the

WM task, participants responded to the location of a green or a red square (left or right). For responses to the presence of a green square, the corresponding key was spatially congruent with the location of the square (e.g. a left hand response to a square located on the left), while for the red square the incongruent response pattern applied, hence increasing the cognitive control required for inhibiting a congruent response (which was also increased by making the green square appear more often than the red square). Following a response, two trials of a simple flanker task with a target letter and a peripheral distractor letter were performed, and the crucial aspect was whether the distractor in the first trial was of the same identity as the second target (inducing negative priming) or not. It was found that for trials where cognitive control functions were exhausted due to the spatial incongruency of the red square and hand of response, the negative priming effect was eliminated, whereas spatially congruent trials resulted in clear negative priming in the subsequent flanker trials. The absence of negative priming under high WM load indicates that as executive functions were exhausted, the distractor could no longer be successfully inhibited, which usually results in the pattern of negative priming.

Early Influence of WM load on Perceptual Processing

The role of available WM capacity was originally considered to affect processing at a late selection stage (i.e. in low perceptual load tasks), in that WM was proposed to be important for the maintenance of task priorities such as making a response to the target rather than to the competing distractor which has been processed (e.g. Lavie et al., 2004). However, recent studies have demonstrated a similar effect of WM as previously described, but on processing of distractors that are completely irrelevant to the task as they do not share any features with the target, which makes it possible that the influence of WM load may operate at an earlier stage than at the time of response (as argued by De Fockert, 2013; De Fockert & Bremner, 2011). For example, Lavie and De Fockert (2005) investigated the role of WM availability in determining attentional capture by irrelevant singleton distractors. Whilst maintaining a digit set of high or low WM load, participants indicated the direction of a line within a target in a visual search task where the target was defined by shape. The presence of an irrelevant singleton distractor of a different colour from the other stimuli resulted in slower RTs compared to when it was absent. Crucially, this cost was significantly larger under high versus low WM load. Thus, the results suggest that the extent to which attention-capturing singletons impede performance depends on the availability of WM – even when the distractors are of no relevance at all to the task (in comparison to the response competition paradigms where the distractor is somewhat relevant as it shares the same response category as the target). The influence of WM load on attentional capture was further supported in an fMRI study which demonstrated an involvement of frontal cortex in suppression of interference from a task-irrelevant yet salient singleton (Lavie & de Fockert, 2006). Thus, loading WM – which is heavily associated with activity in the frontal cortex – is likely to lead to increased distractor interference even when the distractor is entirely task irrelevant. The fact that the distractor did not compete with the target for control of response (due to it not sharing any features with the target) further suggests that the influence of WM load on selective attention may have occurred at an earlier processing stage than that of response selection (e.g. De Fockert & Bremner, 2011).

The availability of WM capacity has also been found to influence the occurrence of inattentional blindness (De Fockert & Bremner, 2011). Participants performed a classic inattentional blindness task (e.g. Cartwright-Fitch & Lavie, 2007), judging the lengths of the arms of a cross whilst memorising a string of numbers either in random order (high WM load) or sequential order (low WM load). It was found that the frequency of inattentional blindness in the presence of a critical stimulus was reduced when WM was loaded, which means that a greater proportion of identifications was evident under high WM load. Similarly to these findings, a recent investigation into awareness of critical stimuli was carried out, but this time with expected and also more meaningful stimuli (Carmel, Fairnie, & Lavie, 2012). Participants performed a similar task to the categorisation task used by De Fockert et al. (2001) whereby a name of a famous person appeared on the screen and a judgement of whether the name belonged to a politician or a singer was made whilst ignoring an anonymous distractor face. This task was performed whilst keeping either a string of random digits (high WM load) or one digit (low WM load) in mind. On the final trial, the anonymous face was replaced with a famous face, and subsequently a surprise question appeared where participants had to make a judgement from two famous faces which face was presented on the final trial. There was a significant increase in the frequency of correct identifications under high (vs. low) WM load, providing further suggestion that with a higher WM load a failure to stay on task results in increased processing of irrelevant distractors which in this case led to a positive identification. The finding remained when the response competition between the famous name and the critical face was eliminated as participants categorised words into kitchen and garden tools. What is even more interesting is that the WM load effect diminished when the meaningful distractor faces were replaced with buildings, such that identification on the surprise question of a famous building was no longer greater under high (vs. low) WM load. This indicates that the role of available WM capacity may only be of importance if the irrelevant stimuli are meaningful enough to cause distraction.

However, in contrast to the above findings demonstrating a decrease in inattentional blindness during a high WM load task, Fougnie and Marois (2007) reported an opposite pattern of results. More specifically, a higher occurrence of blindness was seen in relation to a critical stimulus on the final trial when participants had to mentally rearrange a sequence of five random letters (high WM load) compared with when they simply had to memorise the order of the letters (low WM load). However, there are some aspects of their study which does not make it directly comparable to the two studies reporting conflicting results (i.e. Carmel et al., 2012; De Fockert and Bremner, 2011). Firstly, the study only consisted of the WM task rather than a dual task setting, which is typically used when measuring the influence of WM load on irrelevant distractor processing. This means that the appearance of the critical stimulus occurred in isolation from any other visual stimuli (during the retention period). One study has suggested that the influence of WM load on distractor processing only holds when there is sufficient competition between the relevant stimuli and the distractor (Macdonald & Lavie, 2008). This might explain why there was no increase in detection as the WM task got more demanding, but it fails to account for why a reduction in detection indeed was seen. However, there is a potential explanation for this pattern of results based on the nature of the WM task. Both tasks involved memorising each spatial position of the letters, such that the probe letter appeared in one out of five positions and participants had to make a judgement as to whether that letter had originally appeared in that particular position. Thus, the task might have engaged visual short term memory (VSTM) rather than WM load, which could explain why a reduction was seen under high VSTM compared with low VSTM (as argued by Carmel et al., 2012). In fact, manipulation of VSTM has been shown to have similar effects as manipulation of perceptual load, such that interference decreases with an increase in VSTM load (Konstantinou et al., 2012), lending further support to this possibility.

Taken together, these findings seem to imply that WM can also influence earlier stages involving perceptual processing (as argued by De Fockert, 2013; De Fockert & Bremner 2011) rather than only influencing post-perceptual response stages. This is in line with a recent finding suggesting that WM load alters the spatial focus of attention such that with less availability of WM capacity, the attentional window gets smeared as the perceptual resources are not as strongly focused on a narrow spatial location (Caparos & Linnell, 2010). Thus, it seems plausible that this change in the attentional window as a function of WM load leads to an increase in processing of irrelevant stimuli rather than simply making it more difficult to respond to the relevant stimuli in the presence of irrelevant distractors.

The Influence of WM load on Auditory Distractor Processing

The fact that the role of WM load has spanned over such a wide range of tasks with different measures of controlled attention further strengthens its critical role in determining whether task focus can be maintained despite the presence of distracting stimuli. However, similarly to the existing literature on perceptual load, most work on WM load has been confined to the visual domain. Nevertheless, a few recent studies have addressed the importance of available WM resources in ignoring irrelevant distractors in the auditory domain (e.g. Dalton, Santangelo, & Spence, 2009; Dittrich & Stahl, 2011). For example, in one study, participants responded to the elevation of a continuous target sound (high or low) while ignoring a pulsed nontarget sound which was also at a high or low elevation (Dalton et al., 2009). The selective attention task was preceded by a WM load task which consisted of a sequence of six digits, either in random (high WM load) or in ascending order (low WM load). After participants performed the elevation discrimination, a probe digit appeared which was part of the memory set rehearsed, and participants indicated what digit had followed it in the sequence. When the distractor sound was at the opposite elevation from that of the target, RTs were slower compared to when the target and the distractor shared the same elevation. Crucially, this distractor interference effect in RTs was larger under high (vs. low) WM load, which suggests that WM load plays a similar role in hearing as it has been widely demonstrated to play in vision (e.g. De Fockert et al., 2001; Lavie et al., 2004). However, no study to date has investigated whether the same role of WM would hold for processing of distractors that have no relation to the target at all (unlike Dalton et al.). In particular, it is important to extend the findings to such a setting as it has previously been argued (e.g. De Fockert, 2013) that the influence of WM load on the processing of entirely irrelevant distractors might operate at an earlier stage of processing than at the point of response which tasks measuring response competition might reflect. This is what I aim to investigate in Chapter 4.

Individual Differences in Auditory Distractor Processing

The introduction has so far reviewed the literature relating to the role of perceptual load and working memory load on the extent to which processing of both visual and auditory distractors occurs. One common assumption within many cognitive psychology studies (including the majority of attention research) is that performance is equal between participants, which means that results are typically confined to group average. However, this assumption does not always hold true. For example, one recent study attempted to more closely investigate the role of perceptual load on visual distractor processing by not only considering the results at group level but also at an individual level (Fitousi & Wenger, 2011). While load theory was supported in the RT data at the group level, only half of the participants demonstrated the pattern of results in line with the predictions of the theory (i.e. reduced distractor processing under high load). This inconsistency is likely to reflect individual differences in processing strategy under high and low load.

Given that there seems to be individual variability in performance on selective attention tasks (e.g. Fitousi & Wenger, 2011), the question remains whether this difference relates at all to individual differences outside the laboratory. Since selective attention tasks typically are strikingly different from real life behaviour – for example due to the setting often involving hundreds of repetitions of the same task, using stimuli much less complex than what is commonly processed – it is important to investigate whether the performance measured relates at all to everyday behaviour.

The cognitive failures questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982) is a commonly used measure of individual differences in everyday life. The questionnaire involves 25 items describing typical everyday blunders (e.g. “Do you fail to notice signposts on the road?”; “Do you find you forget why you went from one part of the house to the other?”), and participants indicate on a Likert scale the frequency with which each item has occurred to them within the past six months. The score provides a measure of everyday distractibility, and the higher the score the more commonly do they experience these blunders. CFQ score has previously been linked with performance on visual selective attention tasks. For example, in a visual flanker task which varied the perceptual demands, high scorers demonstrated greater distractor processing under low perceptual load than low scorers, which established a clear relationship between distractor interference and everyday distractibility (Forster & Lavie, 2007). Furthermore, the high perceptual load task eliminated these individual differences as distractor interference was reduced across participants.

Although previous studies have reported a relationship between performance on a visual selective attention task and everyday distractibility, the question remains what underlying factors determine the extent to which an individual experience cognitive failures. In both hearing and vision, a number of studies have investigated the role of working memory capacity on the ability to maintain task focus. Working memory capacity has typically been quantified using the operation span task (OSPAN; Turner & Engle, 1989), which involves solving simple mathematical problems while rehearsing a number of words. The amount of words correctly recalled at the end reflects the working memory span score, and typically the highest and lowest scorers are used. For example, it has been demonstrated that low span participants show more distractor interference than do high span participants in a visual Stroop task when incongruent trials are rare (Kane & Engle, 2003). This suggests that high span participants are better at remaining task-focused (i.e. ignoring the word and responding to the colour) compared to those with a lower span. Furthermore, the influence of WM load on high versus low WM span participants has also been investigated using a standard WM load paradigm consisting of active rehearsal of digits while performing a visual selective attention task (Ahmed & De Fockert, 2012a). For those with high WM span, distractor interference increased under high WM load. However surprisingly, although the low capacity participants showed much larger interference effects under low WM load than did the high span group, distractor interference decreased significantly under high WM load for the low span group. This was suggested to relate to the spatial distribution of attention which may be influenced by the availability of WM capacity. In general, it seemed that the spatial focus of attention was less confined to a narrow location as WM load increased. However, for the low capacity group the spatial profile of attention was spread to such an extent that distractor processing in fact was reduced. This is in line with other findings from Ahmed and de Fockert (2012b) whereby increased WM load resulted in less interference from local distractors in a Navon task (i.e. when participants attended globally), whereas the opposite pattern was observed when participants attended locally, such that increased WM load resulted in more interference from the global distractors. This is thought to relate to the smearing of the attentional window as WM load is increased, resulting in processing of the global feature of the Navon figure even when trying to focus on the local feature.

In hearing, the role of WM capacity has been investigated in a dichotic listening task. Given that only a small proportion of participants reported hearing their own name in the early studies investigating the cocktail party effect (e.g. Moray, 1959), Conway et al. (2001) set out to replicate the findings of Moray while more closely examining what role WM capacity plays in the ability to stay focused on the relevant channel. Similarly to Moray, participants shadowed the message presented to one ear whilst ignoring the message presented to the other ear, and the crucial task manipulation was the presentation of their name in the unattended ear. It was demonstrated that the low WM span scorers were significantly more likely to process their name in the unattended ear than were the high scorers. Thus, it seems that a high WM capacity results in a greater ability to remain focused on the relevant task stimuli. Furthermore, in a similar study whereby participants not only were asked to shadow one channel but also told to listen out for their name in the other ear, the high span participants detected their name with much greater frequency than did the low span participants (Colflesh & Conway, 2007). This suggests that high span individuals not only are better at focusing attention, but also at dividing attention whenever required.

The findings demonstrating a role of WM capacity on distractor processing both in hearing and in vision might suggest that the underlying factor in the differences between occurrences of everyday distractibility relates to individual differences in WM capacity. If this holds true, it is likely that everyday distractibility as measured through the CFQ questionnaire might predict distractor processing in the auditory selective attention tasks, just as it does in tasks of visual attention, because the effects of WM are likely to operate at a supra-modal level. This has previously not been examined. In Chapter 5, I will investigate whether such a similar relationship between reported blunders and auditory distractor processing exist.

The Influence of Reward on Attention

So far, the chapter has reviewed the relative role of perceptual load and WM load as determinants of selective attention, followed by an account of how individual differences might influence the extent to which distractor processing occurs. This section will move on to consider another potential determinant of selective attention which has received a large amount of focus in recent years, namely the role of monetary rewards (Anderson, 2013). For example, it has been shown that the magnitude of the attentional blink changed as a function of a previously learned value association (reward or punishment) with the target (Raymond & O'Brien, 2009). More specifically, targets previously associated with a high reward were detected with a higher frequency than did those which were associated with a lower reward, demonstrating a great occurrence of attentional blinks. This clearly suggests a strong influence of associated rewards on the extent to which attention is focused. However, the separate contribution of reward and attention can be hard to disentangle in some experimental set-ups, as optimal task performance resulting in high reward might simply reflect an increase in goal-directed attention rather than an automatic effect of reward which acts to modulate the focusing of attention (e.g. Maunsell, 2004). Nonetheless, a number of recent studies have suggested that reward can affect visual processing and attentional selection beyond the influence of increased top-down control associated with a stronger motivation to stay task-focused (e.g. Anderson, Laurent, & Yantis, (2011b). For example, it has been demonstrated that reward can influence the level of activation in areas of visual cortex reflecting early processing of stimuli such as V1 responding to the learned value of a particular stimulus (Serences, 2008). This finding indicates that associated reward has the ability to manipulate processing of stimuli at an earlier stage than what simply a bias towards a particular stimulus based on its associated reward would perhaps predict.

However, no studies to date have investigated whether reward can have the same influence on auditory processing, which I will aim to investigate in the final experimental chapter. Although the literature attempting to delineate whether an effect of reward can be genuinely different than a strong top-down influence of attention for a stronger focus on stimuli associated with a high reward versus a low reward is of great importance, the focus on the work in this thesis is to first of all determine whether reward can influence attentional selection. A particularly good measure of strength of attentional selection towards a relevant target amongst competing nontargets can be obtained using ERPs. In particular, the N2pc component is used to provide a marker of spatial selection towards a target (or a salient non-target sharing a feature with the target, e.g. Luck & Hillyard, (1994a; 1994b). The N2pc is often measured in visual search tasks whereby participants attempt to make discrimination towards a target based on a unique feature, whilst ignoring competing distractors. The defining feature of the N2pc is a larger negative voltage over posterior electrodes in the hemisphere contralateral to the location of the target, arising around 200-300 ms after target onset. Because the N2pc is thought to reflect the allocation of spatial attention towards a target, it is a suitable measure of the influence of reward on attentional selection.

Indeed, the N2pc has previously been used to establish the timing of selective attention influenced with the associated reward towards a target (e.g. Kiss, Driver, & Eimer, 2009; Hickey, Chelazzi, & Theeuwes, 2010). Kiss et al. (2009) used a visual search task, whereby the target-defining feature (i.e. colour; red or green) was associated with a high or a low reward. Participants made judgements as to whether a notch on the target appeared at the top or the bottom of the shape. Results revealed a greater negativity and also an earlier onset of the N2pc in response to targets associated with a high reward (vs. a low reward). This suggests for a strong influence of the associated reward, both on the timing and strength of attentional selection in vision.

Although the N2pc reflects visual spatial allocation of attention, a recent study has identified an auditory component which might reflect a similar process to that in vision (Gamble & Luck, 2011). Two sounds were simultaneously presented, and participants made judgements as to whether a predetermined target was present or absent. For target present trials, there was an enhanced negativity over anterior electrodes in the hemisphere contralateral to the spatial location of the target sound which began around 200 ms after onset of the bilateral stimuli. Due to its anterior location, it was coined the N2ac. Although one cannot be certain based on one study alone that the N2ac reflects similar attentional processes as the visual N2pc, it nevertheless offers an opportunity to investigate the timing and strength of allocation of spatial selection towards a relevant sound when presented with a competing sound. Thus, I will use the N2ac component as a marker of selection towards a target sound and further investigate whether the strength or the timing of the N2ac is any different depending on whether participants are anticipating a potential high or low reward.

Some Methodological Considerations

I will end this introduction by presenting a number of methodological considerations that have informed the design and methodology of the experiments reported in this thesis. Given that many of the present studies are based largely on visual findings, it is important to consider the nature of auditory processing and how it differs from visual processing when designing analogous auditory experiments.

The Nature of Auditory Processing

Whereas the visual system prioritises the processing of stimuli that fall on the fovea, the auditory system can pick up sounds arriving from any location, and also in the dark. Hence, one might argue that there is an even greater need within audition for the ability to organise the input into separate perceptual units. Bregman (1990) proposed that the auditory scene is analysed through two stages. Initially, the different sound sources are grouped based on common characteristics such as perceptual similarities (e.g. pitch, timbre and spatial location) and whether the sounds share a common onset/offset. These are then integrated to form individual streams. Following this, the attention can then be focused on the most relevant stream in the auditory scene. However, it has more recently been argued that attention can also affect the earlier formation of auditory objects (Shinn-Cunningham, 2008).

Although it might be tempting to assume that the perceptual organisation in audition is highly similar to that in vision, it is important to consider the fundamental differences in processing between the two senses (e.g. Neuhoff, 2003). For example, it has been argued that the auditory system seems to possess a greater temporal resolution, while the visual system has a greater ability for spatial organisation (Welch & Warren, 1980). This ties in with the fact that whereas the areas of the cortex involved in visual processing are spatiotopically organised, the auditory cortex is mainly organised according to frequency (Merzenich, Colwell & Andersen, 1982), which suggests that spatial processing is not as prioritised in hearing as it is in vision. Based on the idea that spatial location is processed in audition with lower priority than, for example, frequency and timing, it has been argued that separation of auditory stimuli over time might be comparable with spatial separation of visual stimuli (e.g., Kubovy, 1981).

However, although these obvious differences exist in the very early processing levels of auditory and visual stimuli, it is important to note that more similar processes are likely to exist at a higher level of processing (e.g. Dyson, 2009). This is supported by the fact that auditory attention appears to operate through a selective focus on auditory objects or streams (e.g. Shinn-Cunningham, 2008) in line with similar claims from the visual domain about object-based attention (Duncan 1984). Furthermore, many attentional phenomena are evident in both vision and hearing, such as inattentional blindness/deafness (e.g. Mack & Rock, 1998; Dalton & Fraenkel, 2012), change blindness/deafness (Simons & Levin, 1997; Vitevitch, 2003), attentional blink (Raymond, Shapiro, & Arnell, 1992; Tremblay, Vachon, & Jones, 2005) and inhibition of return (Schmidt, 1996; Posner, Rafal, Choate, & Vaughan, 1985). Thus, it is not unreasonable to think that visual and auditory selective attention might be subject to some of the same influences, as investigated within this thesis. However, the basic differences in processing priorities between vision and audition are useful to consider when designing tasks based on findings from the other sensory modality.

Spatial Separation in Auditory Selective Attention

Given the considerations above, the majority of the experiments within this thesis use temporal separation of auditory stimuli. However, some other important design considerations required the use of simultaneous presentation methods in some of the studies described in Chapters 2, 5 and 6 (see the chapter introductions for detailed discussions of the reasons for these design decisions). This design choice brings with it a range of methodological considerations.

Spatial separation between relevant and irrelevant sounds has been shown to enhance the ability to selectively attend to the former. For example, Broadbent (1954, cited in Scharf, 1998) noticed that when two passages of speech were presented simultaneously, participants could more readily and accurately follow the relevant channel when the two were written to different, well-separated loudspeakers, or to separate earphones compared with presenting both channels to the same speaker or earphone. Spatial auditory attention has also been investigated through studies of spatial orienting. For example, Spence and Driver (1994) presented participants with either exogenous or endogenous cues in an auditory discrimination task. When the task involved localisation of a target sound, there was a marked benefit for both types of cues if they were presented on the same (vs. opposite) side as the appearance of the target sound. Thus, spatial orienting of attention, regardless of whether it was automatic (exogenous) or voluntary (endogenous) led to a slight increase in performance in the auditory task. In relation to the present research questions, this finding suggests that knowing where to listen can improve performance, which is particularly relevant in a setting where several sound sources appear from different locations. Presenting a target in a known location can therefore make the task easier to perform than having the target randomly appearing in different locations.

However, it is worth noting that not all studies have found an advantage of spatial orienting in auditory selective attention. For example, Lowe (1968) found no difference in detection of a signal depending on whether participants were aware of what direction the sound was appearing from. Another example was reported by Posner (1978) whereby a spatial cue did not enhance auditory processing, while this was the case when the task stimuli were either visual or tactile.

Although the results on this question seem somewhat mixed, the balance of findings appears to suggest that spatial separation of simultaneously-presented stimuli can lead to enhanced processing of relevant (over irrelevant) stimuli in audition, even though the auditory system prioritises space to a lesser extent than vision. For this reason, whenever simultaneous presentation methods are used within this thesis, the sounds are separated clearly in space. This is of particular relevance for the experiments investigating perceptual load, because load theory specifically highlights the importance of ‘physical distinction’ – such as spatial separation – between relevant and irrelevant stimuli in determining the efficacy of selection in visual settings (Lavie, 1995). Although Lavie clearly underlined that such a distinction does not in itself determine successful selection, as does perceptual load, she argued that it might be a necessary aspect as it allows for successful selection and aids in prioritising processing of relevant stimuli.

The Nature of Auditory Masking

Another important aspect to consider for the experiments described within the thesis is the likely influence of auditory masking within the designed tasks. This section therefore describes the principles of masking and discusses the ways in which the occurrence of masking can be reduced.

When focusing on a specific sound, for example when following a particular voice, this task can often be interfered by competing sounds which lead to reduced perception of the relevant sound. The two most common factors involved are referred to as energetic and informational masking. Energetic masking relates to the degradation of a sound in the presence of others which share considerable overlap in frequency. The effect of energetic masking occurs through suppression at a cochleal level (where frequency selectivity takes place). Informational masking, on the other hand, concerns the similarity between two or more competing sounds and the difficulty in determining and focusing upon the relevant sound. As Leek, Brown, and Dorman (1991, p. 205) phrase it, “informational masking is tied to a listener’s ability to ‘find’ the portion of a complex sound that contains the information necessary for successful completion of an experimental task”. Additionally, in contrast to energetic masking, the sounds do not have to be presented simultaneously for informational masking to occur. For complex sounds, there is often a combination of the two masking types involved in the inability to clearly perceive and extract the relevant sounds – although in terms of competing speech informational masking may be more prominent. Masking will therefore pose a problem in the current research, especially for the presentation of simultaneous sounds. Although masking may occur in a temporal manner too (e.g. Scharf, 1971), one can safely predict that the amount of masking would be similar across perceptual load, as long as the presentation rate remains constant between the two conditions.

For a simultaneous presentation of stimuli, perceptual load is commonly manipulated by variations in the number of the stimuli presented in the set display. As a result of this, one could predict that the occurrence of masking will not be equal between the two levels of perceptual load, and an apparent effect supporting the theory may in fact be due to masking rather than a genuine role of load. It is therefore vital to attempt to reduce the appearance of masking as much as possible. This was carried out through consideration of three factors which have been highlighted as being particularly important in affecting the levels of masking observed in different conditions: spatial separation, number of stimuli and physical difference between target and masker.

Release of informational masking has been demonstrated through increased spatial separation between the target and competing sounds, both when they constitute speech (e.g. Arbogast, Mason, & Kidd, 2002; Brungart & Simpson, 2002; Freyman, Helfer, McCall, & Clifton, 1999; Freyman, Balakrishnan, & Helfer, 2004) and nonspeech stimuli (Kidd, Mason, Rohtla, & Deliwala, 1998). For example, Freyman et al. (1999) demonstrated a more prominent advantage of spatial separation in the perception of a female target when the interfering sound consisted of a female voice, compared to nonspeech noise. This finding suggests that informational masking is reduced, but also to a greater extent than is energetic masking, when perceived spatial separation between sounds occurs. It has also been demonstrated that the release from masking through spatial separation not only occurs on an azimuthal level but also based on separation in distance (Brungart & Simpson, 2002). Ericson, Brungart and Simpson (2004) demonstrated that in an experimental setting with multiple talkers, spatial separation between each talker improved performance on responding to a single talker, especially when prior information of target talker's voice and location was revealed. For this reason, whenever auditory stimuli are presented simultaneously within this thesis, they are clearly separated in space, with the aim of reducing any masking occurring between them.

The number of masking talkers also plays a large role in whether one can remain focused on the relevant talker in that informational masking interferes with speech comprehension to a greater extent the more talkers, but only up to three masking talkers. Any number above shows a decrease in informational masking (Carhart, Johnson, & Goodman, 1975). Unfortunately, some aspects of the design of Experiments 1 and 2 did require variations in the number of talkers, meaning that some effects of masking are likely in those experiments (as discussed in more detail in Chapter 2). However, these effects were avoided in all subsequent experiments. Interestingly, the effects of spatial separation and number of talkers have been shown to interact. For example, Freyman et al. (2004) demonstrated that release from masking due to spatial separation in settings with multiple talkers is decreased if the number of masking talkers rises above two – in which case performance is improved when the sounds are presented at the same location. It was not possible to incorporate these findings into the design of Experiments 1 and 2 because it was important to keep spatial separation constant as the speaker numbers increased (from low to high load), as discussed in more detail in Chapter 2.

The final means through which masking was addressed in the current thesis concerns the physical differences between target and masker. Specifically, less informational masking is seen as the physical difference between target and masker increases. For example, more masking occurs for two talkers of the same sex compared to two talkers of different genders (Brungart, 2001). Furthermore, two individual talkers of the same gender are easier to separate than two simultaneous streams coming from the same person (Brungart). Voice characteristics also matter to a great extent, as it was demonstrated that, for example, change in fundamental frequency in the voice of the same talker – when two different streams of speech are presented simultaneously – leads to improvement in speech segregation when the difference is over two semitones (Darwin, Brungart, & Simpson, 2003). However, this improvement in performance was still not equal to performance with two talkers of different gender. For this reason, simultaneously-presented speech stimuli were distinguished by gender of speaker wherever possible in the current work. In addition, where non-speech stimuli were used (e.g. in Chapter 6) these were made as physically distinct as possible.

Overview of Experimental Chapters

The aim of the thesis was to explore potential determinants of auditory selective attention that have been established in vision. To this end, Chapters 2 and 3 examined whether perceptual load theory could determine the extent to which irrelevant auditory stimuli receive any processing. While Chapter 2 manipulated auditory perceptual load by varying the number of items in the relevant display, the experiments in Chapter 3 changed the perceptual similarity between the target and nontargets. Chapter 4 investigated whether WM load would play a role in the ability to maintain task focus in the presence of auditory distractors which were completely irrelevant to the task at hand. While the other chapters focused on performance at a group level, Chapter 5 investigated individual differences in everyday distractibility and whether these could predict level of distractor processing in a laboratory task measuring auditory selective attention. Finally, Chapter 6 examined whether an associated monetary reward would influence the efficiency of target selection when two auditory stimuli were presented simultaneously. Compared with all other chapters reporting findings from behavioural studies, Chapter 6 also used EEG to more closely investigate the influence of a monetary reward.

Chapter 2 – Auditory Perceptual Load, Manipulated Through the Number of Items in the Relevant Task

Introduction

In the first two experiments reported in this thesis I sought to investigate the role of perceptual load in hearing. This is particularly pertinent because firm conclusions regarding the applicability of load theory in hearing cannot presently be made based on previous findings (e.g. Alain & Izenberg, 2003; Francis, 2010; Gomes et al., 2008), as I discussed in more detail in the previous chapter. To summarise, firstly, the results have been mixed, and secondly some studies have suffered from potential confounds. For example, the use of different presentation rates could have altered the strength of perceptual segregation between high and low load (Gomes et al., 2008). Furthermore, changes between low load and high load in processing strategy for a relevant stream may also have affected processing of the irrelevant stream, ultimately affecting distractor processing (e.g. Alain & Izenberg, 2003). Thus, I aimed to use task-setups that were not subject to similar potential confounds.

I closely followed the operational definitions of perceptual load theory with the aim of ensuring that the experimental levels of load reflected a true manipulation of perceptual demands. To this end, I manipulated perceptual load by varying the number of stimuli – in this instance letter sound utterances – in the relevant set display. This is a manipulation of perceptual load which has been widely used in the visual domain (e.g. Lavie, 1995; Murphy et al., 2012). A common low perceptual load task set-up involves the presentation of a target letter on its own in one of six spatial locations along a row. Conversely, under high load five nontarget letters of different identity engage the remaining five locations. Thus, more perceptual resources are needed to identify the target under high (vs. low) load. A distractor letter which is congruent, incongruent or neutral is simultaneously presented in the periphery. According to perceptual load theory, when the target letter is presented on its own (low load) and consequently is not consuming all available processing capacity, the distractor letter should be processed. In contrast, there should be reduced distractor processing under high load due to the increased perceptual demand of the relevant task.

In line with these previous visual manipulations, both experiments reported in this chapter used a set display which consisted of either a target letter presented on its own (low load) or a target presented alongside a nontarget (high load). Although a common visual manipulation would consist of at least four simultaneously presented items (one target, three nontargets) to induce a high perceptual load setting (Lavie & Cox, 1997), the set-up used in the present experiments had a lower number in order for each sound to be audible. An irrelevant distractor letter sound — either congruent or incongruent with the target identity — was also presented along with the relevant sounds. In Experiment 1, the distractor remained absent on one third of the trials. This condition was included to provide a performance baseline which would allow for a clear comparison as to whether distractors produce task interference or facilitation. As a neutral distractor could produce salience related interference despite having no direct relevance to the target letter (e.g. Caparos & Linell, 2010), a target absent condition could provide a better measure to compare against when considering the directionality of distractor processing. Similarly to Francis (2010), the irrelevant distractor was spoken in a voice of the opposite gender (in this case, male) to that of the target and nontarget sounds (female) in order to create a clear perceptual separation between them. Furthermore, the target was centrally presented, while the nontarget (under high load) and distractor (if present) each appeared from either left or right speaker, but never from the same speaker. An additional motivation for the presentation of each sound from a different spatial location comes from previous findings demonstrating that potential masking can be reduced if there is a spatial separation between the different sources (e.g. Freyman et al., 1999), as I discussed in more detail in the previous chapter.

The prediction of the two experiments reported in this chapter was that if perceptual load theory also holds in hearing, distractor interference measured through response competition would be expected to occur to a significantly greater extent under low load than under high load.

Experiment 1

Experiment 1 used a target discrimination task, in which participants identified a target letter (X or N) spoken in a female voice. The high perceptual load task also included a simultaneously presented peripheral non-target letter spoken in the same voice, whereas under low load this non-target remained absent. A peripheral distractor letter sound — either congruent or incongruent with the target — could also be presented concurrently with the relevant sounds.

Method

Participants

Fifteen participants (two males) were recruited at Royal Holloway, University of London, in exchange for course credits. The average age was 20, ranging from 18 to 24 years. Two (one female, one male) were left-handed. Participants in all experiments described in this thesis reported normal or corrected-to-normal vision and normal hearing. Informed consent was obtained from all participants and all testing protocols were approved by the Departmental Ethics Committee.

Apparatus and Stimuli

The experiment was programmed and run on a PC using the PST E-prime 2.0.8.90 software. Sounds were presented on Sony SRS – A201 speakers which were placed in line with the ear position on each side of the head, 40 cm apart from each ear. The auditory stimuli consisted of single letter sounds, which were selected from stimuli used by Shomstein & Yantis (2006). To ensure that sounds onset and offset simultaneously, the individual letter stimuli for each trial were merged in to single stereo .WAV files. Stimuli were presented at an average level of approximately 60 dB SPL. The length of each letter sound was edited to 240 ms, followed by a 10 ms silence such that the total duration was 250 ms. Mono source recordings of the target letter (X or N, spoken in a female voice) were written to both channels, so that the target's perceived location was at the centre of the stereo field (see Francis, 2010, for a similar method of determining stimulus location). In the high load condition, an additional nontarget letter (either A, C, K, T, U, or Y) spoken in the same voice as the target was written to either the left or the right channel. The distractor letter (X or N) was simultaneously presented with the relevant sounds on two thirds of the trials. The distractor stimulus was written to either the left or the right channel, but it was never written to the same channel as the nontarget letter, if present. See Figure 1 for a visual description of the task set-up.

The identity of the target letter was equally likely to be X or N, and the six nontarget letters also appeared with equal likelihood. The distractor letter was equally likely to be absent, congruent with the target or incongruent with the target. The spatial positioning of the nontarget letter and the distractor letter was fully counterbalanced.

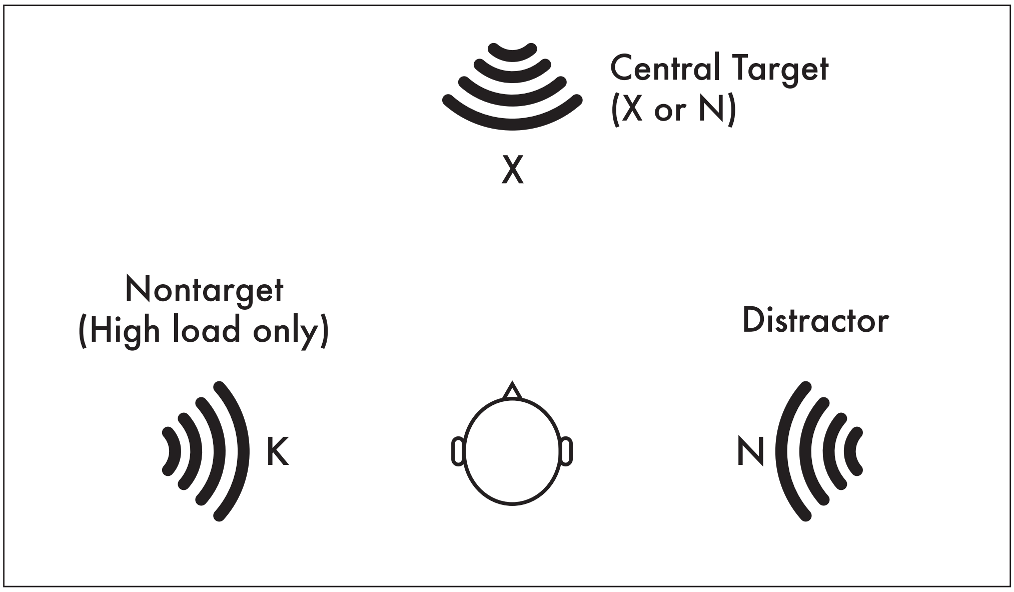

Figure 1. Example of the task in Experiment 1, in which the target (X or N) always appeared in the central position in relation to the participant's head. The nontarget (under high load) and the distractor (X or N; if present) were presented from either the left or the right speaker, but never from the same speaker.

Procedure

Each participant was tested individually in a quiet testing room. Participants were asked to attend to the female voice only and to completely ignore the male voice, and also to focus their attention towards the centre, as the target letter would always appear centrally. In terms of task performance, there was an equal emphasis on speed of responses and on accuracy expressed to the participants. Half of the participants pressed the 0 key on the numerical keyboard with their right index finger whenever they heard the target letter N and the 2 key with their right middle finger whenever they heard the target letter X. For the other half of the participants, the correspondence between the response key and the target letters was inversed. 500 ms prior to and during each trial, a grey fixation cross was presented centrally on the screen on a black background, which remained throughout the trials. The fixation helped to control for eye movements, and potential head movements during the task were controlled for by a chin rest. Immediately after response on each trial, visual feedback appeared on the screen for 500 ms. The feedback consisted of “Correct” presented in blue letters for correct responses, “Oops” in red letters for incorrect responses, and “No response detected” in blue letters if participants had failed to respond within 3000 ms from the onset of the letter sounds. A new trial commenced after the feedback, with the re-appearance of the fixation cross.

The participants completed two practice blocks in the presence of the experimenter — one high load and one low load block with 24 trials in each — in order to make sure that they could perform the task without further practice. If necessary, repetition of the practice blocks was provided. Subsequently, the participants completed ten experimental blocks of 72 trials in each, with self-timed breaks in between blocks. High and low load was blocked, and the order of the blocks was counterbalanced across participants, so that half of them performed the blocks in the order high, low, low, high, while the reverse order of blocks was performed by the other half.

Results and Discussion

Data from two participants were excluded due to below-chance performance in the high load incongruent condition (error rates of 75% and 54%), suggesting that they could not perform the task successfully. Furthermore, data from another participant were excluded due to problems in data recording. For the remaining 12 participants, incorrect responses and responses above 2.5 s were excluded from the reaction time analysis, which eliminated 1.1% of the total number of trials. In all subsequent experiments, note that the cut-off was adjusted (2 or 2.5 s) to ensure that the total percentage of trials excluded were similar in order to allow for a strong comparison between experiments. When applicable, a Bonferroni corrected alpha of $p < .017$ (to follow up a significant main effect with three levels) and $p < .025$ (to correct for the two ANOVAs following up a significant two-way interaction) was used to account for multiple testing. The mean RTs and error rates across participants were calculated for each of the experimental conditions, presented in Table 1.

RTs

The mean RTs were entered into a 2 (load: high, low) × 3 (distractor congruency: congruent, absent, incongruent) repeated measures ANOVA. There was a significant main effect of load, $F(1,11) = 39.83$, $MSE = 19021.8$, $p < .001$, $\eta_p^2 = .784$, with slower responses in the high load condition ($M = 880$ ms) than in the low load condition ($M = 675$ ms). This indicates a successful manipulation of perceptual load. There was also a main effect of congruency, $F(1.18, 12.93)$, $= 12.73$, $MSE = 3676.31$, $p < .01$, $\eta_p^2 = .536$, Greenhouse-Geisser corrected. (The same correction was applied throughout this thesis whenever the sphericity assumption was violated). RTs were significantly slower in the incongruent condition ($M = 813$ ms), compared to the distractor absent condition ($M = 746$ ms), $t(11) = 3.89$, $p < .01$, $d = .329$, and also in contrast to the congruent condition ($M = 772$ ms), $t(11)$, $= 6.56$, $p < .001$, $d = .194$. RTs were not significantly different between the congruent and distractor absent conditions, $t(11) = 1.82$, $p = .097$, $d = .118$. Most importantly, there was a significant load × distractor congruency interaction, $F(2,22) = 8.09$, $MSE = 3109.51$,

$p < .01$, $\eta_p^2 = .424$. A post-hoc one-way repeated measures ANOVA revealed no significant effect of congruency in the high load condition, $F(2,22) < 1$, $\eta_p^2 = .035$,. However, a significant effect of congruency was seen in the low load condition, $F(2,22) = 21.06$, $MSE = 2357.96$, $p < .001$, $\eta_p^2 = .700$. Pairwise comparisons demonstrated that under low load, participants were significantly slower when the distractor was incongruent than when it was congruent, $t(11) = 4.14$, $p < .01$, $d = .336$, or absent, $t(11) = 5.06$, $p < .001$, $d = .649$. RTs were also significantly slower when the distractor was congruent, compared to the distractor absent condition, ($t(11) = 3.67$, $p < .01$, $d = .307$. Since distractor interference was reduced under high load (vs. low load), the RT results were in line with the claims of load theory.

However, as RTs were overall slower under high (vs. low) load, it was important to establish that the reduction in distractor interference was not due to a scaling effect. Similarly to Francis (2010), distractor interference (incongruent – congruent) was expressed as a percentage of mean RT separately for each load condition (low, 10.2%; high, 2.2%). The difference between high and low load was marginally significant, $t(11) = 2.14$, $p = .056$, $d = 1.045$, suggesting that the reduction in distractor interference under high (vs. low) load was not due to an overall slowing in responses, in line with load theory.

Table 1. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 1 as a function of perceptual load (low, high) and distractor congruency (congruent, absent, incongruent). SDs are in brackets.

	Distractor Congruency		
Perceptual Load	Congruent	Absent	Incongruent
Low			
Mean RT	669 (201)	613 (162)	742 (227)
% Errors	4 (.03)	3 (.03)	7 (.04)
High			
Mean RT	875 (241)	879 (244)	885 (210)
% Errors	7 (.04)	8 (.05)	21 (.12)

Error Rates

However, while the RT results provided initial support for load theory, the pattern of error rates was in the opposite direction. Mean error rates for each condition were calculated and analysed with a 2 (load: high, low) × 3 (distractor congruency: congruent, absent, incongruent) repeated measures ANOVA. As with the RTs, there was a significant main effect of load F(1,11) = 23.40, MSE = .004, $p < .001$, η_p^2 = .680. Participants were overall less accurate in the high load condition (M = 12%) compared to the low load condition (M = 5%), which further suggested that the perceptual load manipulation was successful. A significant main effect of distractor congruency was also demonstrated, F(1.23, 13.55) = 19.79, MSE = .005, $p < .001$, η_p^2 = .643. Participants were significantly less accurate in the incongruent condition (M = 14%), compared to both the congruent (M = 6%), t(11) = 4.67, $p < .001$, d = 1.512, and the absent conditions (M = 6%), t(11) = 4.56, $p < .001$, d = 1.491. However, there was no significant difference in errors between the distractor absent and the congruent conditions, t(11) < 1, d = .031. Similarly to the RT analysis, there was also a significant interaction, F(1.37, 15.01) = 14.40, MSE = .002, $p < .001$, η_p^2 = .567. However, contrary to the RTs, a post-hoc one-way repeated measures ANOVA revealed a significant effect of congruency under high load, F(1.24, 13.69) = 18.33, MSE = .007, $p < .001$, η_p^2 = .625. Pairwise comparisons revealed that the error rate in the incongruent condition was higher than the absent condition, t(11) = 4.3, $p < .001$, d = 1.562 and the congruent condition, t(11) = 4.61, $p <.001$, d = 1.492. There was no difference in error rate between the congruent and absent conditions, t(11) < 1, d = .090. A similar ANOVA on data from the low load condition also revealed a significant effect of congruency, F(2,22) = 11.85, MSE = .0003, $p < .001$, η_p^2 = .519. Pairwise comparisons demonstrated a significant increase in errors in the incongruent distractor condition compared to both the distractor absent condition, t(11) = 3.9, $p < .01$, d = .884, and the congruent condition, t(11) = 3.8, $p < .01$, d = .751 which did not differ from each other, t(11) = 1, p = .339, d = .196.

Inverse Efficiency Analysis

Overall, the RT results demonstrated a significant reduction in distractor processing under high load (vs. low load), as predicted by load theory. However, the predicted pattern in the RTs was reversed in the error rates, as distractor interference was larger under high load than under low load. As this opposite trend between the error rates and the RTs could suggest potential speed/accuracy trade-offs, an additional analysis of inverse efficiency (Townsend & Ashby, 1983), which takes into account both RTs and accuracy, was performed. Calculations of scores were performed in line with previous research (Akhtar & Enns, 1989; Goffaux, Hault, Michel, Vuong & Rossion, 2005) whereby mean RTs of each participant for each experimental condition were divided by the accuracy rates (see Table 2). Scores are measured in ms and higher scores indicate less efficient performance. The inverse efficiency scores were entered into a 2 (load: high, low) × 3 (distractor condition: absent, congruent, incongruent) repeated measures ANOVA. A main effect of load was revealed, $F(1,11) = 30.4$, $MSE = 57108.32$, $p < .001$, $\eta_p^2 = .734$. As expected, performance was worse under high load ($M = 1026$) than under low load ($M = 715$), indicating a clearly successful manipulation of perceptual load. There was also a significant main effect of congruency, $F(1.2, 13.21) = 15.76$, $MSE = 25147.3$, $p < .001$, $\eta_p^2 = .589$. However, none of the following tests of simple effects reached significance after Bonferroni correction. In contrast to previous analyses, there was no significant load × congruency interaction, however this was to be expected due to the reversal of the effect in the RTs compared to error rates, $F(1.27, 14.01) = 1.73$, $MSE = 16608.65$, $p = .213$, $\eta_p^2 = .136$.

Table 2. Inverse efficiency scores (RTs divided by error rates) for Experiment 1 as a function of load (low, high) and distractor congruency (congruent, absent, incongruent). SDs are in brackets.

	Distractor Congruency		
Perceptual Load	Congruent	Absent	Incongruent
Low	702 (235)	640 (198)	804 (282)
High	954 (293)	959 (293)	1165 (408)

However, while this inverse efficiency analysis provided a useful means for investigating this potential speed/accuracy trade-off, it is important to note that there are also issues with such an approach. For example, this type of analysis is less reliable with error rates over 10% (Townsend & Ashby, 1983), which is the case in the high load incongruent condition (see Table 1). Nevertheless, although these findings should be taken with caution, they do confirm what was already predicted based on the pattern of RT and error data – namely that, when both performance measures are taken together, there is no clear evidence in support of load theory from this experiment.

In conclusion, although the data from the RT analysis were in line with the predictions made by the perceptual load theory, the reversal demonstrated in the error rates weakens the impact of the RT results, making it difficult at this stage to draw any conclusions in support of perceptual load theory. The results demonstrated distractor interference under both levels of perceptual load, although this was manifested differently for the two conditions. For low load, distractor interference was evident in both the RT and error data, while under high load this was only reflected in the error patterns. The fact that interference was seen in the error rates but not in the RTs under high load may reflect the adoption of a ‘deadline strategy’, whereby a response was made at a specific time point regardless of whether or not participants had fully processed the target sound. It seems plausible that participants might have used a strategy of this type under high (but not low) load conditions in response to high levels of task difficulty associated with the presence of an additional nontarget letter under high load. Therefore, the aim of Experiment 2 was to match accuracy more effectively across conditions, which in turn would allow for a clearer comparison between task performance under high and low load.

Experiment 2

In order to increase overall task accuracy by comparison with Experiment 1, I increased the spatial separation and frequency differences between all stimuli in order to boost their perceptual discriminability. Furthermore, the distractor was present on all trials to reduce the possibility that it might capture attention due to its comparative novelty when it only appeared on a number of the total trials. The experiment was otherwise very similar to Experiment 1.

Method

Participants

16 new participants (three males) were recruited. Two were left-handed (two females) and the average age was 21 (ranging from 19 to 28).

Stimuli and Procedure

The stimuli were similar to Experiment 1, with the following exceptions. Contrary to Experiment 1 which used speakers, stimuli were presented via Sennheiser HD 202 headphones to further enhance the spatial separation between the sounds. The letter sounds were presented at an average sound level of approximately 55 dB SPL. The target letter sounds were changed to N and T, so that they were easy to discriminate from the point of onset (in contrast to X and N which have similar onsets). The average frequencies of the targets were increased by one semitone to make them more easily distinguishable from nontargets (A, F, G, K, U, Y) under high perceptual load. The average frequencies of the distractors were reduced by half a semitone to distinguish them more effectively from targets and nontargets. Finally, the distractor absent condition was excluded in order to reduce the possibility that the distractor sound might capture attention. Thus, a distractor was now present on every trial.

The procedure was identical to Experiment 1, except that fewer trials were needed with the exclusion of the distractor absent condition. Two practice blocks of 24 trials in each were run, followed by ten blocks of 48 trials in each.

Results and Discussion

Two participants were excluded from the analysis due to mean RTs of 818 ms and 833 ms, which were over 2 SDs slower than the group mean RT (M = 521 ms; SD = 137). RTs above 2000 ms were also excluded (< 1% of the total number of trials). Table 3 shows RTs and error rates as a function of perceptual load and distractor congruency.

RTs

A 2 (perceptual load: low, high) × 2 (congruency: congruent, incongruent) repeated-measures ANOVA on the RT data revealed a significant main effect of load, $F(1,13) = 16.84$, $MSE = 3037.67$ $p < .001$, $\eta_p^2 = .564$. RTs were slower in the high load condition (M = 507 ms) compared with low load (M = 447 ms), indicating that the perceptual load manipulation remained successful despite the changes to the experiment. There was also a main effect of congruency, $F(1,13) = 5.59$, $MSE = 212.18$, $p < .05$, $\eta_p^2 = .301$, with RTs slower in the incongruent (M = 482 ms) than in the congruent condition (M = 473 ms). However, there was no load × congruency interaction, $F(1,11) < 1$, $\eta_p^2 = .013$, indicating that the successful load manipulation did not affect the extent to which the irrelevant distractors were processed.

Table 3. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 2 as a function of perceptual load (low, high) and distractor congruency (congruent, incongruent). SDs are in brackets.

	Distractor Congruency	
Perceptual Load	Congruent	Incongruent
Low		
Mean RT	443 (60)	451 (62)
% Errors	2 (.04)	2 (.02)
High		
Mean RT	502 (83)	513 (78)
% Errors	3 (.03)	4 (.04)

Error Rates

A similar analysis was run for the error rates, which found no effect of load, F(1,13) = 3.84, MSE = .001, p = .072, η_p^2 = .228, or of congruency, F(1,13) = 2.16, MSE = .0001, p = .166, η_p^2 = .142. Similarly to the RT analysis, there was no significant load × congruency interaction, F(1,13) = 3.67, MSE = .0002, p = .078, η_p^2 = .220, and any trend towards an interaction was in fact in the opposite direction to what was predicted by load theory.

The aim of Experiment 2 was to match the accuracy between the two load conditions more closely, in order to allow a clearer examination of potential load effects in the RT data. The lack of a main effect of load in the error rates indicated that this aim was successful (see Table 3). However, despite a successful manipulation of perceptual load reflected in the RTs, distractor congruency was not significantly different between the two conditions of perceptual load. This finding is in line with the results in Experiment 1 which found no overall evidence of an effect of perceptual load on auditory distractor processing.

However, it is of importance to note that although overall accuracy increased in Experiment 2, the overall congruency effect was reduced when compared with Experiment 1. Thus it could be that even though a significant congruency effect was evident, the actual interference from the distractors was too small to allow any effects of perceptual load to be revealed. In vision, it has been established that it is crucial that the distracting stimuli are not too distinguished from the relevant task-set as they will otherwise not produce any interference at all (e.g. Lavie & Tsal, 1994). It may therefore be the case that, although the Experiment 2 task no longer seemed to suffer from large differences in task difficulty between high and low load in Experiment 1, it instead suffered from the distractor not being distracting enough to cause interference effects that would be open to modulation by perceptual load.

Chapter Discussion

Experiments 1 and 2 set out to investigate whether perceptual load can determine the extent to which auditory distractor processing occurs. The two experiments manipulated perceptual load by varying the number of letter sounds in the task display. Overall, there was a failure to find a reliable effect of perceptual load on auditory distractor processing. Although the RT results in Experiment 1 converged with the typical findings from previous visual research on this question, the findings remain problematic given the reverse pattern seen in the error rates. It is therefore more likely that the significantly reduced distractor interference demonstrated in the RTs under high perceptual load instead was a reflection of a deadline strategy adopted by participants. It seems plausible that the additional nontarget in the high load displays might have made the task sufficiently difficult to encourage participants to respond after a certain period of time, whether or not they had fully completed the required processing. This possibility was strengthened by the fact that when measures were taken in Experiment 2 to improve task performance (by increasing the frequency separation and enhancing the spatial discrimination between the sounds) there was no longer a pattern in the results suggestive of a perceptual load effect. Instead, it seemed that distractors were processed to the same extent regardless of the perceptual demands employed by the task (although it is important to note that the overall congruency effect was smaller in this instance).

The overall failure to find any support for perceptual load theory in hearing clearly contradicts the findings of Francis (2010) who also used a simultaneous presentation and a similar method of obtaining a clear spatial separation between stimuli. Over two experiments, Francis found some evidence for a reduction in distractor processing under high load (requiring processing of feature conjunctions) by comparison with low load (requiring processing of single features). However, as previously mentioned, there was no sign of a significant interaction between load and distractor congruency as $F < 1$ in both of the experiments, and the only support in favour of perceptual load theory was evident when comparing differences between conditions. This lack of the interactions predicted by load theory ultimately weakens the strength of Francis's findings. It is nonetheless of importance to acknowledge that the pattern of the results was indeed in line with the predictions of perceptual load theory, which to this date is the most promising pattern of findings.

It is important to note that the overall congruency effects were markedly larger in Francis's (2010) experiments (with an average congruency effect of 118 ms for Experiment 1 and 111 ms for Experiment 2) than in the present experiments (with mean effects of 67 ms for Experiment 1 and 9 ms for Experiment 2). It is thus possible that any measurable effect of perceptual load would only be observed in experimental set-ups which involve large distractor interference effects. It was therefore important to design a new task set-up which could potentially lead to larger overall congruency effects, and this formed one of the aims of the experiments described in the following chapter.

Another difference between the present experiments and those carried out by Francis (2010) was the choice of load manipulation. While I manipulated perceptual load through the number of items in the relevant display, Francis altered the perceptual processing demands through the use of a feature-based task (low load) vs. a conjunction-based task (high load), while keeping the stimuli constant. Although perceptual load effects in vision have been demonstrated with a range of different load manipulations (e.g, Lavie, 2010), it may be that only some manipulations are able to affect distractor processing in a similar way in hearing due to the inherent differences in how visual and auditory stimuli are processed. In order to provide a more definitive test of whether the same principles of perceptual load hold in the auditory domain, it was important to test the theory using a different load manipulation. This was a second aim of the experiments described in Chapter 3.

Although most investigations into the role of perceptual load in visual selective attention have used a simultaneous presentation of stimuli which have all been spatially separated, it may be that this presentation method is not the most suitable for investigating perceptual load in an auditory setting. For example, Cusack and Carlyon (2003) have argued that space is not as prioritised in early auditory perceptual grouping than it is in vision (although once sounds have been segregated, spatial information can be used to selectively attend to a particular portion of the input; e.g. Darwin & Hukin, 1999) and Kubovy (1981) suggested that a temporal separation between sounds might be comparable to a spatial separation between visual objects. It may therefore be more suitable to present sounds with a temporal rather than spatial separation to more directly compare auditory selective attention with the equivalent visual processes. This approach was taken in the experiments in the next chapter. However, it is important to note that the design of the present experiments did not rely on spatial separation alone, but also involved separation by voice type, whereby distractors were presented in a male voice and targets and nontargets were presented in a female voice. The relevant and irrelevant sounds will therefore also have been separated by frequency, in the sense that the male voice will have had a lower average frequency than the female voice. Given that frequency has previously been suggested to play a more pivotal role in auditory selection than spatial location (e.g. Kubovy, 1981; Woods, Alain, Diaz, Rhodes, & Ogawa, 2001), this additional separation by voice may partly have counteracted the issue with the spatial separation.

It is also worth mentioning that, despite the potential problems in equivalence between the effects of simultaneous presentation of auditory and visual stimuli, Francis (2010) nevertheless demonstrated perceptual load effects using a task involving simultaneous presentation of sounds. However, in his experiments the number of auditory objects in the task set-up remained constant across perceptual load conditions. By contrast, in the two experiments reported in this chapter, the high perceptual load condition involved the presentation of an additional auditory object by comparison with the low load condition. What is problematic in this instance is that the amount of masking is likely to have been unequal across perceptual load conditions. Indeed, it seems plausible that masking effects could have contributed to the apparent 'deadline strategy' observed under high perceptual load in Experiment 1. Therefore, another motivation for the change to a sequential presentation method in the following experiments was that this set-up both reduces the likelihood of substantial influences of masking on performance and ensures that any residual masking effects are matched between high and low load conditions. However, although both experiments in this chapter are likely to have been influenced to some extent by masking effects, it is important to note that in Experiment 2 the difference in frequency between the distractors and the targets and nontargets was increased, which is likely to have reduced the influence of masking in that experiment (e.g. Darwin et al., 2003).

These measures may also have contributed to the reduced congruency effects seen in Experiment 2. It seems likely that the distractors were no longer as interfering as they had been in Experiment 1 at least partly because they were more clearly differentiated from the targets in terms of frequency. However, it is also likely that the increased spatial separation between stimuli due to the use of headphones (rather than loudspeakers) in Experiment 2 might have contributed to the reduced congruency effects. For example, the use of headphones is likely to have allowed greater perceptual segmentation between streams of sounds, perhaps meaning that participants could more successfully focus in on the central locations from which the target reliably arrived in each trial. One final factor that is likely to have contributed to the reduced congruency effects in Experiment 2 is the removal of the distractor absent condition. Because the distractor was now present on each trial, there may have been a greater ability to successfully ignore it due to its predictable appearance (although note that the distractor location was not predictable on a trial-by-trial basis). Regardless of the cause of this reduction in distractor processing, it remains problematic as it could be that the congruency effects were in this instance simply too small to reveal a true effect of perceptual load. For this reason, the following experiments also aimed to increase the magnitude of the overall congruency effects observed.

One final difference between the current auditory task and its visual equivalents is that in the current experiments the spatial location (left vs. right) of the nontarget letter was unpredictable. By contrast, in a typical visual setting, the target and nontargets would be allocated a specific spatial location, although the exact location of each stimulus would vary randomly between trials. Lavie (1995) argued that load importantly should be manipulated in the ‘relevant processing’ as it is the perceptual demands of the relevant information that determine whether selection occurs early or late, rather than for example the perceptual properties of the irrelevant information. Thus, the spatial formation of a display set defines where the relevant processing occurs. However, this spatial formation is not directly equivalent in the present experiments to the typical visual display sets. Although the target letter always appeared from the same location, the potential location of the relevant nontarget (left or right) could also be the location of the irrelevant distractor. This is different from the visual set-ups, in which a distractor would always appear in a position where no relevant stimuli were presented. However, the relevant and irrelevant stimuli were clearly separated in terms of the voice of the speaker (male versus female) which arguably could have acted as a stronger selection cue for the auditory system than the spatial location of sounds (e.g. Kubovy, 1981; Woods et al, 2001).

Chapter 3 – Auditory Perceptual Load, Manipulated Through the Perceptual Similarity Between Target and Nontargets

Introduction

The previous chapter investigated the role of perceptual load in determining the extent to which processing of irrelevant auditory distractors occurs. Both experiments failed to find any support for the applicability of load theory to the auditory modality. However, the experiments employed a task set-up in which all sounds were presented simultaneously, which may not have been the most appropriate setting for perceptual load effects to be revealed. In fact, the majority of studies on auditory selective attention tend to present stimuli in a sequence rather than simultaneously (e.g. Alain & Izenberg, 2003; Cusack & Carlyon, 2003; Gomes et al., 2008). Furthermore, it has been argued that temporal separation between stimuli might be comparable with spatial separation of visual stimuli (e.g. Kubovy, 1981). Therefore, this was the approach taken in the following experiments.

As with Experiments 1 and 2, the aim was to closely follow the operational definitions of perceptual load when designing the task. However, rather than changing the number of items in the relevant set, perceptual load was now manipulated by varying the perceptual similarity between the target and the nontarget sounds. In the visual domain, equivalent studies have typically used a display set consisting of a circle of six letters (e.g. Lavie & Cox, 1997; Forster & Lavie, 2008; Beck & Lavie, 2005). Under low load, the target letter (e.g. X or N) is easily distinguishable from the five nontargets which are of the same identity (often o's) which means that few perceptual resources are depleted in identifying the target (resulting in the surplus capacity spilling over to process irrelevant stimuli). By contrast, the high load display contains nontarget letters of different identities that are angular in shape and similar in appearance to the target. Thus, more perceptual resources are needed to identify the target in such a setting (leaving no surplus capacity for distractor processing).

Although most studies have used this load manipulation with a simultaneous presentation of stimuli, a more recent visual study demonstrated that perceptual load effects could also be observed using a sequential presentation where stimuli do not overlap in time (Carmel, Thorne, Rees, & Lavie, 2011). Participants focused on a stream of crosses in different colours and orientations. Apart from detecting a target cross which was defined by colour under low perceptual load and a conjunction of colour and orientation under high perceptual load, participants also reported the presence of a critical stimulus appearing in the periphery, but never at the same time as the appearance of a target. Report of the critical stimulus was reduced under high load (compared with low load), which is in line with predictions of load theory and accords with findings from the simultaneous setting (e.g. Lavie & Cox, 1997; Forster & Lavie, 2008; Beck & Lavie, 2005). These findings are also of importance in relation to the current experiments as they suggest that stimuli do not necessarily need to overlap in time for perceptual load to have an effect, as long as they occur while perceptual processing is still ongoing.

Interestingly, Carmel et al. (2011) also ran a crossmodal version of the experiment, using an auditory presentation of syllables, spoken in a male or a female voice. Participants responded to a specific syllable regardless of voice under low load, while under high load they responded to a conjunction of syllable and voice. In contrast to the visual experiments, detection of the critical visual stimuli did not differ as a function of perceptual load, despite a successful load manipulation. Although this finding is in line with the results from Chapter 2 of this thesis (and also with Gomes et al., 2008), it may be that the lack of a load modulation relates to the crossmodal nature of the task. Indeed, there are other failed attempts at finding a crossmodal modulation of perceptual load (e.g. Rees et al., 2001; Tellinghuisen & Novak, 2003), suggesting that perceptual load effects may be modality-specific (although conflicting findings exist; e.g. Macdonald & Lavie, 2011). However, the fact that the task successfully manipulated load with a sequential presentation of sounds is encouraging for the present aim of investigating auditory perceptual load in a unimodal setting.

An added strength of using a sequential presentation is that this allows each stimulus to be presented with a unique onset and also at a clearly defined spatial location. This is likely to increase the perceptual discriminability between targets, nontargets and distractors, which should improve task performance. Furthermore, as the distractor also will benefit in terms of discriminability due to its unique onset, distractor processing is likely to increase in this task set-up. This is particularly important given that Experiment 2 demonstrated a distractor interference which may have been too weak to reveal a possible load modulation.

While the experiments in Chapter 2 are likely to have suffered from differences in amount of simultaneous masking between high and low load (because the high load condition included an additional letter sound), the sequential experiments in this chapter are not likely to suffer from such potential confound. However, it is worth noting that masking can also occur between two non-simultaneous sounds (e.g. Oxenham & Wojtczak, 2009), both ‘forward’ (when the first of two sequential sounds masks the second) and ‘backward’ (when the second of two sequential sounds masks the first) masking. Even though forward and backward masking does not completely remove processing of the masked sound, partial masking effects can occur (e.g. Scharf, 1971), such that the perceived loudness of the masked sound is reduced. This type of partial masking is likely to occur for up to 100 ms after the onset or offset of the masking sound. Although this means that some non-simultaneous masking is possible in the present experiments, because the ISIs are briefer than 100 ms, this should not be as problematic as in Chapter 2 because the amount of masking is likely to be similar between high and low perceptual load.

The three experiments reported in this chapter presented sequences of six letter sounds. Similarly to the visual experiments, nontarget letters under high perceptual load were similar-sounding to the target letters which made it increasingly taxing to identify the target. Conversely, the target letters were easily identifiable amongst the nontarget letters under low load. A distractor sound was presented from a different location mid-way through the sequence.

Experiment 3

Method

Participants

16 new participants (2 males, one left-handed) were recruited in exchange for course credits or a monetary reward of £5. The average age was 23 years, ranging from 18 to 40.

Stimuli and Procedure

The apparatus, stimuli and procedure were as described for Experiments 1 and 2, with the following exceptions. Each trial consisted of a rapid sequence of six centrally-perceived letters in a female voice (presented simultaneously from the left and right speakers). Participants made button-press discrimination responses according to the identity of a target letter (P or T, with equal likelihood) which was present on each trial. The target was never presented in the first or last serial position and was equally likely to appear at any of the four remaining serial positions. Participants were asked to respond as soon as the target letter was perceived, rather than listening to the full sequence prior to responding.

In the high perceptual load condition, the five nontarget letters making up the rest of the sequence were drawn at random (without replacement) from a list of six letters (A, C, H, G, J, and K). In the low perceptual load condition, the five nontarget letters were all X’s. Letters were separated by silent ISIs of 60 ms, resulting in a total duration of 1740 ms for each sequence.

A distractor letter appeared on two thirds of the trials, at the mid-point of the sequence (i.e. in between the third and the fourth letter sound). The onset of the distractor sound occurred 150 ms after the onset of the third letter sound, to enable a symmetrical overlap of the distractor with the third and the fourth sound. Thus, the distractor overlapped with the final 90 ms of the third letter and with the initial 90 ms of the fourth letter. While the letter sequence was presented binaurally, the distractor was presented monaurally, appearing from the left or right speaker with equal likelihood. Similarly to Experiment 1 and 2, the distractor letter was spoken in a male voice, and it was either congruent with the target (one third of trials) or incongruent (one third of trials). On the remaining third of the trials, the distractor remained absent. See Figure 2 for a visual description of the task set-up. The participants completed two practice blocks of 12 trials each, followed by ten experimental blocks of 48 trials in each.

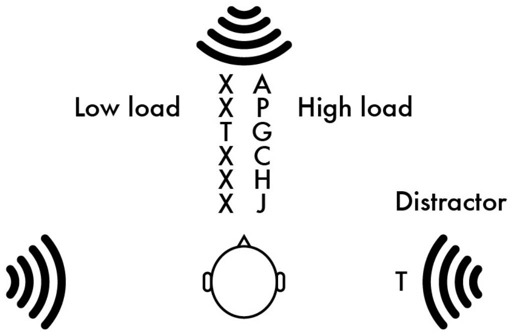

Figure 2. Example of a low and a high load trial, in which the target (P or T) randomly appeared in position 2-5 of the centrally presented sequence. The distractor sound (P or T) was presented from either the left or the right speaker.

Results and Discussion

Data from one participant were excluded due to technical problems in data recording. Similarly, data from an additional participant were not included in the analysis as mean RTs (M=855 ms) were more than 2 SDs higher than the group mean RTs (M=550 ms, SD=112). For the remaining 14 participants, incorrect responses and responses above 2000 ms (1% of the total number of trials) were excluded from the RT analysis.

RTs

A 2 (perceptual load: low, high) × 3 (distractor congruency: congruent, absent, incongruent) repeated measures ANOVA on the RT data revealed a significant main effect of perceptual load, $F(1,13) = 11.36$, $MSE = 3936.57$, $p < .01$, $\eta_p^2 = .466$. Participants were slower in their responses in the high load condition ($M = 551$ ms) in comparison with the low load condition ($M = 505$ ms), indicating that the load manipulation was successful. There was also a significant main effect of distractor congruency, $F(1.21, 15.71) = 14.51$, $MSE = 1012.13$, $p < .001$, $\eta_p^2 = .527$. Responses were slower in the incongruent condition ($M = 546$ ms) compared to the distractor absent condition ($M = 526$ ms, $t(13)$, 4.33, $p < .001$, $d = .251$) and also in comparison to the congruent condition ($M = 511$ ms, $t(13)$, 3.99, $p < .01$, $d = .454$). There was a near-significant difference in RTs between the congruent and the absent conditions, $t(13)$, 2.7, $p = .018$, $d =.214$ (confidence interval of .017), with slower responses in the absent condition. However, there was no significant perceptual load × distractor congruency interaction revealed, $F(2,26) = 1.37$, $MSE = 300.72$, $p = .272$, $\eta_p^2 = .095$ (see Table 4).

The overall interference effect (calculated by subtracting congruent RTs from incongruent RTs) was equally large under high load (M effect = 36 ms) as under low load (M effect = 35 ms, see Table 4) and an additional t-test confirmed that this interference effect observed under high load was indeed significant, $t(13) = 3.29$, $p < 01$, $d = .436$. The absence of any slight trend towards a reduced interference effect under high load conditions makes it highly unlikely that the failure to find a significant interaction between load and distractor congruency relates to a lack of power.

This finding remained consistent in a further analysis which was designed to rule out any effects of the overall increase in RT seen under high (vs. low) load. As in Experiment 1, distractor interference (incongruent RT – congruent RT) was expressed as a proportion of mean RT for each load condition (low, 6.7%; high, 6%).

There was no difference in this measure between high and low load conditions, t(13) < 1, d = .117.

Since the distractor sound could either overlap in time with the target or not depending on target position, it was important to establish whether the findings would differ depending on this factor. For this reason, a 2 (perceptual load: high, low) × 3 (distractor congruency: absent, congruent, incongruent) × 2 (overlap: yes, no) was run. The main effect of overlap was not significant (F < 1, $\eta_p^2 = .001$) and neither was the 3-way interaction (F < 1, $\eta_p^2 = .034$). This indicates that the effect of load on distractor processing did not vary systematically as a function of whether the distractor overlapped temporally with the target sound or not.

Table 4. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 3 as a function of perceptual load (low, high) and distractor congruency (congruent, absent, incongruent). SDs are in brackets.

	Distractor Congruency		
Perceptual Load	Congruent	Absent	Incongruent
Low			
Mean RT	486 (75)	507 (85)	521 (88)
% Errors	7 (.05)	7 (.05)	7 (.03)
High			
Mean RT	536 (68)	544 (68)	572 (95)
% Errors	6 (.05)	6 (.07)	8 (.06)

Error Rates

The mean error rates for each experimental condition were similarly entered into a 2 (perceptual load: high, low) × 3 (distractor congruency: absent, congruent, incongruent) repeated measures ANOVA, which revealed no significant main effects of load, F (1,13) <1, $\eta_p^2 = .022$, or congruency, F(1,13) = 2.31, MSE = .001, p = .12, $\eta_p^2 = .151$. Similarly, there was no significant interaction, F(1,13) <1, $\eta_p^2 = .064$.

Overall, this new task with a sequential presentation and a different perceptual load manipulation than that of Experiments 1 and 2 demonstrated strong distractor interference effects and a successful manipulation of perceptual load. However distractor processing was not reduced under high (vs. low) perceptual load. These results are in accord with the findings reported in the previous chapter, extending them to a new experimental paradigm which allowed for a clearer manipulation of perceptual load than the simultaneous task setting (as each sound now had a unique temporal onset and was therefore easily audible). The lack of a load modulation on distractor processing further questions whether perceptual load plays the same role in determining distractor processing in hearing as it has been demonstrated to play in vision. However, as the level of perceptual load is defined through operational definitions, it is difficult to quantify the exact level of load imposed by any particular task. Although perceptual demands were significantly increased under high (vs. low) perceptual load (as was evident from the main effect of load seen in the RT analysis), it remains possible that the load manipulation in Experiment 3 was simply not strong enough to exhaust capacity. As a result, the predicted results of reduced distractor interference under high load (vs. low load) may not have been elicited because the relevant task did not use up all processing capacity. The aim of Experiment 4 was therefore to increase the strength of the load manipulation in order to provide a stronger test than was provided by Experiment 3.

Experiment 4

In order to increase the overall perceptual demands of the task by comparison with Experiment 3, I made the letter sequence presentation more rapid by shortening the duration of all individual sounds so that more perceptual resources were needed for the processing of the auditory stimuli.

Method

Participants

15 new participants (five males) were recruited in exchange for course credits. The average age was 19, ranging from 18 to 22 years. Three participants were left-handed (one male).

Stimuli and procedure

The apparatus, stimuli and procedure were as described for Experiment 3, with the following exceptions. Firstly, the identity of the target letters was G and T, and the nontarget letters were the same as the in Experiment 3, apart from the presence of letter N which replaced letter G as it now constituted a target. Secondly, all the letter stimuli were shortened using the Audacity Software (while keeping all other features constant) so that the duration of each was now 180 ms rather than 250 ms. All other aspects of the experiment were identical to Experiment 3.

Results and Discussion

Data from one participant were excluded from the analysis, as overall accuracy (M=86%) was 2 SDs below the overall group mean (M=95%, SD=.04). Responses longer than 2000 ms (1.1% of the total number of trials) were also excluded from the analysis, and so were all incorrect responses for the RT analysis.

RTs

The data were entered into a 2 (perceptual load: low load, high load) × 3 (distractor congruency: congruent, absent, incongruent) repeated measures ANOVA. There was a significant main effect of load revealed, F(1,13) = 26.19, MSE = 6113.54, $p < .001$, $\eta_p^2 = .668$, with participants being slower in the high load condition (M=651 ms) compared with the low load condition (M=563 ms). As in all previous experiments, this indicates that the perceptual load manipulation was successful. The main effect of congruency was also significant, F(2,26) = 20.08, MSE = 643.63 p

< .001, η_p^2 = .607. Responses were slower in the incongruent condition (M=624 ms) compared to the congruent condition (M=583 ms), t(13) = 6.26, p < .001, d = .477, but not in comparison with the distractor absent condition, (M=615), t(13) = 1.13, p = .28, d = .104. Furthermore, RTs were significantly slower in the distractor absent condition than in the congruent condition (t(13) = 5.33, p < .001, d = .379. However, there was no significant perceptual load × congruency interaction revealed, F(2,26)< 1, η_p^2 = .032 (see Table 5).

As in Experiment 3, the overall interference effect was very similar under high load (M effect = 38 ms) as under low load (M effect = 43 ms). An additional t-test confirmed that the overall interference effect (calculated by subtracting congruent from incongruent RTs) remained significant under high load, t(13) = 3.32, p < 01, d = .63. Again, the failure to find an effect of perceptual load was unlikely to be due to a lack of power.

Also as in the previous experiment, there was no difference in distractor interference effects expressed as a proportion of baseline mean RT between high (6%) and low load conditions (7.4%, t(13) < 1, d = .195).

Table 5. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 4 as a function of perceptual load (low, high) and distractor congruency (congruent, absent, incongruent). SDs are in brackets.

	Distractor Congruency		
Perceptual Load	Congruent	Absent	Incongruent
Low			
Mean RT	536 (83)	576 (102)	579 (102)
% Errors	4 (.03)	4 (.05)	5 (.04)
High			
Mean RT	630 (96)	654 (85)	668 (88)
% Errors	5 (.02)	3 (.02)	8 (.03)

Since the distractor sound could either overlap in time with the target or not depending on target position, it was again important to establish whether the findings would differ depending on this factor. Therefore, a 2 (perceptual load: high, low) × 3 (distractor congruency: absent, congruent, incongruent) × 2 (overlap: yes, no) was run, revealing a significant main effect of overlap, F(1,13) = 13.83, MSE = 1731.66, $p < .005$, $\eta_p^2 = .515$, with slower responses as the distractor overlapped with the target (620 ms) compared to when it did not overlap (596 ms) in time. However, the 3-way ANOVA was not significant, F(2,26) = 1.3, MSE = 1348,87, p = .290, $\eta_p^2 = .091$, again suggesting that RTs were not systematically different depending on whether or not the distractor sound temporally overlapped with the target sound.

Error Rates

An identical analysis was carried out on the error rates, where no significant main effect of load was revealed, F(1,13) < 1, $\eta_p^2 = .063$. There was a significant main effect of congruency, F(2,26) = 6.01, MSE = .001, $p < .05$, $\eta_p^2 = .316$. Participants made more errors in the incongruent condition (M=6%) than in the distractor absent condition (M=4%), t(13) = 3.31, $p < .01$, d = .686, but not compared with the congruent condition (M=4%), t(13) = 1.99, p = .069, d = .531. Error rates were not significantly different between the congruent and the distractor absent conditions, t(13) = 1.35, p = .199, d = .270. Unlike the RT analysis, there was a significant load × congruency interaction, F(2,26) = 5.42, MSE = .001, p, < .05, $\eta_p^2 = .294$. A post-hoc one-way repeated measures ANOVA revealed a significant effect of congruency in the high load condition, F (2,26) = 10.74, MSE = .001, $p < .001$, $\eta_p^2 = .452$. Pairwise comparisons demonstrated that error rates were significantly higher in the incongruent condition (M=8%) compared with the distractor absent condition (M=3%), t(13) = 4.3, $p < .001$, d = 1.6, and there was also a strong trend towards them being significantly higher than in the congruent condition (M = 5%), t(13) = 2.7, p = .019, d = 1.04 (confidence interval of .017). The congruent and the absent condition were not significantly different from each other, t(13) = 1.93, p = .076, d = .554. Conversely, the post-hoc one-way repeated measures ANOVA did not reveal a significant effect of congruency in the low load condition, $F(2,26) < 1$, $\eta_p^2 = .018$. It is important to note that this interaction in the error data is in the opposite direction from the predictions made by load theory, with more distractor interference evident under high load compared with low load.

The overall load effect of Experiment 4 (M = 87 ms) was evidently greater than that of Experiment 3 (M = 46 ms), indicating that the load manipulation was successfully strengthened in the present experiment. Despite this, there was once again no difference observed in distractor interference as a function of perceptual load. This further strengthens the previous findings, demonstrating the same results but with different task manipulations. Although the error rates demonstrated a significant load by distractor congruency interaction, this reflected a greater occurrence of distractor interference under high (vs. low load), which is a reversal of the pattern that would be predicted by load theory.

A possible reason as to why processing of the distractor still was present in the high perceptual load condition (despite a stronger load manipulation than that of the previous experiment) could be that the distractor was not present on each trial and may thus have been particularly salient due to its comparative novelty, enabling it to capture attention even under high load conditions. In order to investigate this possibility, the next experiment presented the distractor on all trials. (Note that, although removing the distractor absent condition did not have an effect in Experiment 2 compared with Experiment 1, this could have been due to other changes in that experiment, such as improving spatial separation through the presentation of the stimuli via headphones compared with speakers, which may have increased the perceptual segregation of the sounds).

Experiment 5

As the aim of experiment 5 was to reduce the possibility of the distractor being too attention-capturing, I presented it on every trial and reduced its intensity compared with the relevant sounds.

Method

Participants

14 new participants (three males) were recruited in exchange for course credits. The average age was 21 (ranging from 19 to 22) and two were left-handed (one male, one female).

Stimuli and Procedure

The stimuli and procedure were identical to Experiment 4, apart from a few exceptions. The absent distractor condition was excluded so that the distractor letter sound was now present on each trial. I also reduced the distractor's intensity by 20% relative to the other sounds, which still made the distractor clearly audible. Participants completed 14 experimental blocks with 32 trials in each, preceded by two practice blocks of 12 trials in each.

Results and Discussion

RTs longer than 2000 ms were excluded (1% of the overall trials) and for the RT analysis, incorrect trials were also omitted.

RTs

A 2 (perceptual load: low, high) × 2 (congruency: congruent, incongruent) repeated measures ANOVA revealed a main effect of load, $F(1,13) = 63.99$, $MSE = 2168.47$, $p < .001$, $\eta_p^2 = .831$. Participants were slower in their responses under high load ($M = 625$ ms) than under low load ($M=526$ ms), providing a strong indication of a successful load manipulation. The main effect of distractor congruency was also significant, $F(1,13) = 39.1$, $MSE = 414.31$, $p < .001$, $\eta_p^2 = .750$, with faster RTs in the congruent condition ($M = 559$ ms) than in the incongruent condition ($M = 593$ ms). Once again, the load × congruency interaction did not approach significance, $F(1,13) < 1$, $\eta_p^2 = .002$ (see Table 6).

Similarly to Experiment 3 and 4, the overall interference effect was equally large under high load (M effect = 34 ms) as under low load (M effect = 33 ms, see Table 6) and an additional t-test confirmed that the effect indeed remained significant under high load, t(13) = 3.31, p < 01, d = .418. Once again, this lack of any suggestion of a numerical difference in the interference effects makes it highly unlikely that the failure to find any interaction between load and distractor congruency would be due to a lack of power.

As in the previous experiments, there was no significant difference in distractor interference expressed as a proportion of mean baseline RT between high load (M = 5.6%) and low load conditions (M = 6.5%, t(13) < 1, d = .167). This further supports the findings from the main analysis, indicating that distractor interference did not differ as a function of perceptual load even when accounting for the overall increase in RT under high load.

Again, an additional 3-way ANOVA was run with the added factor of target and distractor overlap (overlap, nonoverlap) to ensure that performance did not differ systematically between the two. There was a main effect of overlap, F(1,3) = 11.24, MSE = 814.37, p < .005, η_p^2 = .464, with slower RTs when the target and distractor overlapped (M = 585 ms) than when they did not (M = 567 ms). However, similarly to Experiment 3 and 4 the 3-way interaction did not reach significance (F < 1, η_p^2 = .004) which confirms that distractor processing under load did not change as a function of target and distractor overlap (vs. nonoverlap).

Table 6. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 5 as a function of perceptual load (low, high) and distractor congruency (congruent, incongruent). SDs are in brackets.

	Distractor Congruency	
Perceptual Load	Congruent	Incongruent
Low		
Mean RT	509 (79)	542 (75)
% Errors	4 (.03)	5 (.04)
High		
Mean RT	608 (84)	643 (86)
% Errors	5 (.03)	9 (.06)

Error Rates

The error data were entered into a 2 (perceptual load: low, high) × 2 (congruency: congruent, incongruent) repeated measures ANOVA, which revealed a main effect of load, $F(1,13) = 6.75$, $MSE = .002$, $p < .05$, $\eta_p^2 = .342$. More errors were evident for high (M=6%) compared to low perceptual load (M = 5%), providing additional evidence that the load manipulation was successful. There was also a significant main effect of congruency, $F(1,13) = 16.22$, $MSE = .001$, $p < .001$, $\eta_p^2 = .555$, with higher errors in the incongruent condition (M = 7%) compared with the congruent condition (M = 4%). The load × congruency interaction did not reach significance, $F(1,13) = 2.88$, $MSE = .001$, $p = .113$, $\eta_p^2 = .181$, (and note that any apparent trend towards an interaction is once again in the opposite direction to that predicted by load theory, see Table 6).

The aim of Experiment 5 was to reduce the potential attention-capturing feature of the distractor by presenting it on all trials so that its presence was predictable, compared with Experiment 3 and 4 where it only appeared on two thirds of the trials. Despite the predictability of the distractor, its interference on task performance was still no different as a function of perceptual load. This failure to find an effect of perceptual load remained even though overall the load manipulation in Experiment 5 (M = 99 ms) was slightly larger than that of Experiment 4 (M = 87 ms), and nearly twice as large as that of Experiment 3 (M = 46 ms). Thus, despite the distractor being less attention-capturing and the load manipulation being stronger than in previous experiments, there was no evidence of an influence of perceptual load on distractor processing. This finding clearly converges with the previous four experiments reported thus far in this thesis.

Chapter Discussion

Experiments 3, 4 and 5 in this chapter were designed to test whether the findings of Experiments 1 and 2 would generalise to a different experimental paradigm and a different load manipulation. I manipulated perceptual load by varying the physical similarity between target and nontargets while keeping the number of relevant items in the set display constant. All three experiments demonstrated clear manipulations of perceptual load, but no effects of load on distractor processing were observed. As a failure to reveal a significant reduction in distractor processing can potentially be explained by the high load condition not being sufficiently demanding, I strengthened the perceptual load manipulation in Experiments 4 and 5 compared to Experiment 3. Despite the increase in perceptual demands over Experiments 4 and 5, distractor processing remained unaffected by the level of perceptual load. This consistent failure to demonstrate the predicted perceptual load effects suggests that load theory might not apply directly to the auditory modality, in particular when also considering the findings from Experiments 1 and 2. Thus, even though I have used two different task set-ups and two different load manipulations, the findings remain consistent.

The findings also converge with two additional experiments conducted in our research lab (Murphy, Fraenkel, & Dalton, 2013), which measured distractor interference through awareness report rather than response competition. The effect of perceptual load on people’s awareness of a critical event was measured in an inattentional deafness task, where participants responded to targets presented to one ear while ignoring white noise in the other ear. The targets consisted of auditory stimuli which were of long or short duration and of high or low frequency. Similarly to Alain and Izenberg (2003) and Carmel et al. (2011), participants responded to a feature of the target (in this case duration) under low perceptual load, while under high load they responded to a conjunction of duration and frequency. On the final trial, a word was presented without warning in the unattended white noise channel. Over two experiments, it was demonstrated that people's awareness of this critical word stimulus was not affected by the perceptual load of the attended task, providing additional evidence for the claim that perceptual load might not play a similar role in hearing as it does in vision. These findings, along with the consistent results of the five experiments presented so far in this thesis, represent converging evidence across three different task paradigms (including two different measures of distractor interference and three different load manipulations) to support the claim that perceptual load theory might not hold in hearing.

Because these claims rest on demonstrations of null interactions, the possibility will always remain that modulation of distractor processing by auditory perceptual load might be observed if one used even more extreme manipulations of load than those used in these studies. However, the lack of any trend towards an influence of load on distractor processing in any of the five experiments (despite clear increases in perceptual demands between some experiments) makes this possibility seem unlikely. Furthermore, the fact that all experiments consistently demonstrated strong main effects of perceptual load and of congruency indicates that there was sufficient power in the experiments to detect an interaction (should there have been a true effect), strengthening the argument that the failure to demonstrate an interaction is a meaningful finding.

It is worth noting that along with perceptual load theory there is the alternative account of perceptual narrowing. Proctor and Van Zandt (2011) describe perceptual narrowing as a reduction in processing of stimuli presented in the periphery compared with stimuli presented at fixation, which typically occurs during a high level of arousal. This type of perceptual narrowing means that stimuli presented in the periphery are no longer processed to the same extent as stimuli presented at fixation. Thus, high arousal could result in the same effect as high perceptual load (vs. low arousal and low perceptual load): namely that processing of distractor stimuli presented in the periphery is reduced while perceptual narrowing increases. In the current five experiments the targets sounds were always presented centrally while the distractor was presented in the periphery. However, since there was no reduction in processing of the peripheral distractors under any of the experimental conditions, the possible influence of perceptual narrowing can be ruled out.

As discussed in more detail earlier in this thesis, previous studies investigating the applicability of load theory within hearing have produced mixed results. In an ERP study, Gomes et al. (2008) found no evidence for reduced processing of an irrelevant auditory channel when the task stimuli were presented with a faster ISI (high perceptual load) compared with a slower ISI (low load). However, by varying the ISI during auditory presentation, one is also likely to introduce changes in the strength of perceptual grouping (e.g. Bregman, 1990), complicating the interpretation of these results (as argued, for example, by Francis, 2010). Nevertheless, the findings of the five experiments presented so far within this thesis converge with those of Gomes et al., despite using load manipulations that are not open to this confound, lending considerable strength to their claim that load theory might not hold within the auditory domain.

However, conversely to Gomes et al. (2008) and the current experiments, Alain and Izenberg (2003) found some evidence in support of load theory in an ERP study where the presence of a deviant distractor resulted in a smaller MMN amplitude during a high load conjunction-based task by comparison with a low load feature-based task. However, the load manipulation used in this experiment may also have led to broader changes in processing strategy, such that the deviant-defining dimension of duration may have been more strongly prioritised in the low load task (which required a focus only on duration) than in the high load task (in which the focus was divided between duration and tuning). This in turn may have affected processing priorities in the unattended stream, such that the duration deviants would have been more in line with participants’ overall attentional set under low load (where duration was highly prioritised) than under high load (where duration may have been less strongly prioritised). It is therefore difficult to determine whether the results reflect a perceptual load modulation or instead reflect the strategic changes occurring due to the task design. None of the task designs reported so far in this thesis are open to such an alternative interpretation, so my failure to find any results that converge with Alain and Izenberg’s findings might lend strength to the possibility that their results were more related to strategic changes than to perceptual load effects.

The most promising results so far in support of the idea that load theory might apply within hearing were reported by Francis (2010), who found some evidence for an effect of perceptual load on auditory distractor processing in a spoken word classification task. However, the significant difference was based on difference score between high and low load rather than the significant interaction between load and congruency that is typically used to demonstrate load effects. Thus, these findings can only be considered to offer preliminary support for load theory in hearing. Furthermore, the effect is confined to one specific task set-up involving speech integration. By contrast, the findings from the five experiments reported in Chapters 2 and 3 which used two different task manipulations are not in line with Francis. Instead, they converge with the findings of Gomes et al. (2008) to suggest that auditory distractor processing does not seem to be affected by the perceptual demands imposed by the relevant auditory task.

This possibility poses interesting questions about how perceptual demands might be handled in hearing, and how this process may be different from that occurring within vision. Perceptual load theory (Lavie, 1995) suggests that perceptual selection can only take place when all processing capacity has been used up, and it is the perceptual demands of the relevant task that dictates *when* this event occurs and ultimately whether processing of irrelevant stimuli can be avoided. Although the theory is based predominantly on evidence from vision, it has been argued that the same principles are also likely to hold in the auditory domain (Lavie & Tsal, 1994). Conversely, Gomes et al. (2008) provided an alternative conceptualisation of the auditory attentional selection system to explain their lack of any modulation of auditory distractor processing by auditory perceptual load. It was suggested that rather than having a system where perceptual processing is mandatory until all processing capacity is exhausted, the auditory system is more flexible in that more voluntary control can be exerted. This means that spare capacity can be retained for the eventuality that a crucial stimulus appears which would be beneficial to process. However, Gomes et al. did not provide any specific description of the mechanism behind this proposed flexible system.

Instead, it may be that a simpler explanation for the pattern of results demonstrated by Gomes et al. (2008) and in the Chapters 2 and 3 is more fitting. The portion of the total input from a scene that is processed by the visual system is largely determined by what falls on the fovea. Thus, visual processing is to a certain extent physically restricted to a specific area. The auditory system, on the other hand, does not contain an equivalent mechanism allowing for such an extreme focus of processing capacity of one specific part of the auditory input. Bregman (1990) argued that in order to make sense of a complex auditory scene, the acoustic input is segregated into patterns called ‘streams’, largely based on qualities of each sound such as location, frequency and timing. Attention can then be focused on the stream relevant to the task (Shinn-Cunningham, 2008). Even though this provides an effective mechanism for auditory selection, it seems unlikely that it would result in the same focusing of perceptual resources as is evident in vision. Instead, it is possible that some spare capacity remains for the processing of unattended streams. As a result, this might mean that even in a situation where the ongoing task is perceptually demanding, full capacity cannot be allocated to task-relevant stimuli and spare capacity thus remains to process auditory events from other streams. This suggestion would indeed converge with previous claims for hearing acting as an ‘early warning system’ (e.g. Scharf, 1998; Dalton & Lavie, 2004). This claim stems from the fact that hearing is less spatially restricted than the other senses and can also process information in the dark, which makes it particularly useful for detecting important changes in the environment which might otherwise go unnoticed.

Overall, the first two experimental chapters reported in this thesis have consistently failed to find any support for the applicability within hearing of the perceptual load aspects of load theory. Chapter 4 will investigate a different prediction of the theory, whereby loading working memory while performing a concurrent selective attention task should alter the extent to which irrelevant sounds are processed.

Chapter 4 – The Effect of WM Load on Auditory Selective Attention

Introduction

Chapters 2 and 3 provided an extensive investigation into the question of whether perceptual load can determine the extent to which auditory distractor processing occurs, as has been widely demonstrated in vision (e.g. Lavie, 2010). The five experiments consistently failed to demonstrate a modulation of perceptual load on processing of auditory distractors, suggesting that attentional selection may work differently in hearing compared to vision. This chapter will focus on a different aspect of load theory by investigating the role of WM load in auditory selective attention. As described in the introductory chapter of this thesis, the load theory has more recently been expanded to include the role of WM in selective attention, following demonstrations that distractor processing was increased with a concurrent task requiring active rehearsal of random digits (high WM load) in contrast to rehearsal of a single digit (low WM load; e.g. De Fockert et al., 2001; Lavie et al., 2004).

Similarly to perceptual load, investigations into WM load have mainly focused on visual paradigms, apart from a few recent studies (e.g. Dalton et al., 2009; Dittrich & Stahl, 2011). For example, the role of WM resources on the ability to remain focused on a relevant auditory task was investigated, whereby participants responded to the elevation of a target sound (high or low) while ignoring a nontarget sound which was presented at the same (congruent) or different elevation (incongruent) from a different speaker (Dalton et al., 2009). The selective attention task was preceded by the WM set which consisted of a sequence of six digits, either in random order (high WM load) or in ascending order (low WM load). Participants then performed the elevation discrimination task while keeping the WM set in mind. Finally, a probe digit appeared – which was part of the memory set rehearsed – and participants indicated which digit had followed the probe in the original set. When the distractor sound was incongruent with the target, RTs were slower compared to when the target and the distractor were congruent. Crucially, this congruency effect in RTs was larger under high (vs. low) WM load, which suggests that WM might play a similar role in hearing as has been widely demonstrated in vision (e.g. De Fockert et al., 2001; De Fockert & Bremner, 2011; Lavie et al., 2004).

Thus, so far it seems that the findings of perceptual load and WM load differ in terms of whether the influence of each on selective attention is restricted to a specific modality or not. While there is little evidence for a role of perceptual load in hearing, the effects of WM load seem to apply more broadly to different sensory modalities. Indeed, not only has there been support for a similar role of WM in hearing (e.g. Dalton et al., 2009), but similar WM effects have also been observed on tactile distractor interference (Dalton, Lavie, & Spence, 2009), suggesting that the availability of WM resources is important in the ability to stay on task regardless of the sensory modality engaged. Given that perceptual load is thought to operate at an early perceptual level, it is perhaps not surprising that a discrepancy exists between modalities, because the perceptual processing systems for the different modalities are very different. Conversely, WM load is thought to operate at a higher 'executive' level involving task coordination and maintenance of task priorities which presumably should be of importance regardless of sensory modality.

Since only a few studies to date have investigated the role of WM load in hearing (e.g. Dalton et al., 2009; Dittrich & Stahl, 2011), it was important to replicate the findings. However, the main focus of this chapter was to investigate whether WM load also influences auditory selective attention for distractors that are completely irrelevant to the task at hand. Conversely, Dalton et al. (2009) focused on processing arising from distractors somewhat relevant to the task, as the elevation could be congruent or incongruent to the elevation of the target sound. It is thus possible that the effect of WM load was related to the involvement of WM in the attempt to solve the response competition arising from the distractor, rather than perception of the distractor. It is therefore important to establish if the same role of WM holds in a task providing a measure of distractor processing that does not rely on response competition. In vision, this has already been established. For example, Lavie and De Fockert (2005) measured attentional capture by irrelevant singleton distractors in a visual search task. Whilst maintaining a standard WM set, participants indicated the direction of a line within a target in a visual search task where the target was defined by shape. The presence (vs. absence) of an irrelevant singleton distractor of a different colour than the other items slowed the RTs, and this slowing was significantly greater under high (vs. low) WM load. Thus, the results suggest that the extent to which attention-capturing singletons impede on performance depends on the availability of WM in order to prioritise task focus – even when the distractor is of no relevance at all to the task (in comparison with the response competition paradigms).

It is however unclear whether the role of WM in maintaining processing priorities in the presence of a particularly attention capturing singleton would be equivalent in the auditory modality. Given that hearing often is thought to act as an ‘early warning system’, monitoring for changes in the environment (e.g. Dalton & Lavie, 2004; Scharf, 1998), it is possible that singleton distractor processing might be unaffected by the availability of WM resources, because processing of such stimuli in fact could potentially be beneficial for the individual (although not in relation to relevant task performance). Although most research on attentional capture has focused upon the visual domain (e.g. Bacon & Egeth, 1994; Theeuwes, 2004; Jonides & Yantis, 1988), the effect has also been demonstrated in hearing (Dalton & Lavie). A range of experiments involved detecting a target tone presented in a rapid sequence amongst nontarget tones. The target differed from the nontarget sounds on one specific feature (e.g. in terms of intensity or frequency), while the other properties of the tones were identical. An additional sound differing from the target and nontarget sounds on an irrelevant feature appeared in the sequence on half of the trials. RT data in all of the experiments demonstrated that the appearance of an irrelevant singleton resulted in a slowing of responses, which suggests that participants failed to ignore the singleton despite it being entirely irrelevant to the current task priorities. Thus, it is evident that particularly salient sounds can also have an attention-capturing characteristic, similarly to visual singletons. The two experiments reported in this chapter used a similar auditory attentional capture paradigm to investigate whether the role of WM load demonstrated by Dalton et al. (2009) would be present in a task where the distracting stimuli have no relevance at all to the task at hand. Any such findings would provide support for load theory and more specifically for the role of WM in attentional control (Lavie et al., 2004).

Experiment 6

Experiment 6 investigated the role of WM load in maintaining task priorities in the presence of a salient distractor, as measured through an auditory attentional capture paradigm. Participants were presented with a rapid sequence of five tones of which one target tone was either longer or shorter in duration than the remaining sounds. On half of the trials, an irrelevant singleton distractor tone of the same duration as the standard tones but with a higher frequency appeared either immediately before or after the target tone. Participants responded according to the duration of the target (long vs. short) whilst also rehearsing a memory set of five digits, presented either in sequential order (low load) or random order (high load). It was predicted according to load theory (e.g. Lavie et al., 2004) that performance cost in the presence (vs. absence) of the singleton distractor would be larger when participants were engaged with a concurrent high WM load task than when they were engaged with a low WM load task, as exhausting cognitive control capacities under high WM load would make it more difficult to maintain task focus.

However, if task cost is no different as a function of WM load, this will converge with my previous findings failing to find any support for load theory in hearing.

Method

Participants

18 new participants (three males) were recruited in exchange for course credits or a monetary reward. The average age was 19 (ranging from 18 to 25 years) and one (female) was left-handed.

Apparatus and Stimuli

The apparatus used to design and to run the experiment were identical to previous experiments. Auditory stimuli were presented over headphones at an average sound level of approximately 65 dB SPL. The working memory task consisted of five visually presented digits between 1 and 9, presented in either a sequential ascending order (low WM load) or a random order (high WM load). In the low WM load task, the sequence began equally often with 1, 2, 3, or 4. In the high WM load task, digits appeared randomly with equal likelihood in each of the five positions, and every digit could only occur once in the sequence for each trial. The memory probe consisted of a single digit (e.g. 3) and the identity of the probe from the memory set appeared equally often in terms of its position in the sequence, apart from position 5 where the probe never appeared from. Each digit subtended .7° x 1° of visual angle, and the whole sequence was of a visual angle of 5°.

Target and nontarget tones in the selective attention task were all of the same frequency of 440 Hz, while the singleton tone was presented with a frequency of 520 Hz. The duration of the nontarget and singleton tone were 100 ms, while the target was either 50 or 150 ms.

Procedure

Each trial began with a fixation cross for 500 ms presented at the centre of the screen. The memory set was subsequently displayed for 1500 ms followed by a 500 ms mask, and then a blank screen for 1000 ms. Participants were instructed to actively rehearse the set as they were later going to be asked to indicate the identity of a number from the set, based on the order of the sequence. A fixation cross appeared for 500 ms, followed by the sequence of five sounds, all presented with an ISI that varied according to the duration of the sound. More specifically, the duration of each sound plus the subsequent ISI was equivalent of 185 ms, in accordance with Dalton and Lavie's (2004) Experiments 5 and 6. The target always appeared in position 3 or 4 of the sequence, and the singleton sound (if present) appeared in the position immediately before or after the target. Directly following the sequence, a question mark appeared for 500 ms. Participants indicated whether the target tone was of short or long duration by pressing the 1 or 2 key on the numeric keyboard respectively. The reverse response patterns applied to half of the participants. Participants were informed that there might be an odd sound appearing at a different frequency from the rest of the tones, and that failure to ignore it could potentially interfere with task performance. Immediately following the response, or if no response had occurred within 3000 ms, feedback appeared on the screen for 1500 ms. Subsequently, there was a blank screen for 1000 ms followed by a probe digit, presented for 3000 ms. Participants indicated what digit had followed the probe digit in the memory set by pressing the corresponding number 1 to 9 key on the numeric keyboard. The same type of feedback display as for the selective attention task appeared on the screen, followed by a blank screen for 1000 ms before a new trial commenced.

Participants were shown six example trials to familiarise them with the task, followed by 12 practice trials of low WM load and 12 of high WM load. Six blocks – three low WM load and three high WM load – were run with 48 trials in each. Within each block, the combination of target type, target position, singleton presence and singleton position were fully counterbalanced. The block order of WM load was counterbalanced in an ABBA fashion.

Results and Discussion

Data from two participants were excluded as performance on the selective attention task was at chance level (> 50% errors) in both singleton present conditions for one participant, and in the high WM load singleton absent condition for the other participant, which indicates that they were not able to successfully discriminate the target. For the remaining 16 participants, responses slower than 2,500ms on the selective attention task were excluded from the analysis (< 1% of the trials).

Probe

Analysis of error rates indicated a larger occurrence of errors under high WM load (M = 13%) compared with low WM load (M = 2%), t(15) = 4.22, $p < .001$, d = 1.33, suggesting that the WM load manipulation was successful. RT analysis of the memory probe data also revealed significantly slower responses under high WM load (M = 1397 ms) than under low WM load (M = 1190 ms; t(15) = 5.92, $p < .001$, d = .751. Although the RT analysis is less reliable as nine potential response keys were used and speed was not as strongly empathised as accuracy, it is still worth noting that they are in line with the errors in indicating a successful load manipulation.

RTs

Selective attention task. Only trials with a correct response to the memory probe were included in the analysis. Additionally, incorrect trials on the selective attention task were excluded. A 2 (WM load: low, high) × 2 (singleton: present, absent) repeated measures ANOVA revealed no main effect of load, F(1,15) < 1, $\eta_p^2 = .021$, suggesting that overall speed of responding in the selective attention task was not affected by the WM load of the secondary task. The main effect of singleton presence was significant, F(1,15) = 4.58, MSE = 8413, $p < .05$, $\eta_p^2 = .234$, with RTs slower in the presence of a singleton (M = 536 ms) compared with singleton absent trials (M = 487 ms). However, the WM load × singleton interaction was not significant, F(1,15) < 1, $\eta_p^2 = .004$ (see Table 7), failing to provide any indication for a role of WM load on the extent to which attentional capture from a singleton tone occurs.

As the singleton could occur either before or after the target sound, it was important to establish if RTs differed depending on its location in relation to the target position. An additional 2 (WM load: low, high) × 2 (singleton position: before, after) revealed no significant main effect of WM load, F(1,15) < 1, $\eta_p^2 = .026$, nor of singleton position, F(1,15) < 1, $\eta_p^2 = .017$, and no significant interaction, F(1,15) = 1.41, MSE = 3615.02, p = .25, $\eta_p^2 = .086$. This clearly confirms that the position of the singleton in relation to the target did not have an effect on task performance.

Table 7. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 6 as a function of WM load (low, high) and singleton presence. SDs are in brackets. Singleton cost (present – absent).

	WM Load					
	Low		High		Singleton cost	
	Present	Absent	Present	Absent	Low	High
Mean RT	529 (183)	484 (174)	544 (195)	491 (151)	45	53
% Errors	11 (.09)	9 (.12)	12 (.12)	7 (.07)	2	5

Error Rates

A 2 (WM load: low, high) × 2 (singleton: present, absent) repeated measures ANOVA was run on the error rates. As for the RTs, there was no significant main effect of load, F(1,15) < 1, $\eta_p^2 = .018$, while the main effect of singleton was significant, F(1,15) = 6.42, MSE = .003, p < .05, $\eta_p^2 = .300$. The presence of a singleton resulted in more errors (M = 11%) compared to singleton absent trials (M = 8%). Again, the interaction was not significant, F(1,15) < 1, $\eta_p^2 = .047$, providing further support for the claim that WM availability might not be important in determining auditory attentional capture.

Similarly to the RT analysis, an additional 2 (WM load: low, high) × 2 (singleton position: before, after) repeated measures ANOVA was run to investigate whether there were any differences in error rates based on the position of the singleton in relation to the target position. The main effect of WM load was not significant, $F(1,15) < 1$, $\eta_p^2 = .014$, while there was a significant main effect of distractor position, $F(1,15) = 5.84$, $MSE = .005$, $p < .05$, $\eta_p^2 = .280$. More errors were made when the singleton appeared before the target ($M = 13\%$) compared to when it appeared after the target (9%). However, this difference did not change as a function of WM load, $F(1,15) = 1.8$, $MSE = .004$, $p = .199$, $\eta_p^2 = .107$.

In line with the findings of Dalton and Lavie (2004), the presence of the unique singleton distractor resulted in slower and less accurate responses compared with its absence, which suggests that the singleton captured participants' attention despite being entirely irrelevant to the task, leading to a cost in performance. This cost in the presence of a singleton was reliably consistent in the present experiment. However, the magnitude of the cost was not modulated by WM load, which is in direct contrast to the findings reported in the visual modality (Lavie & De Fockert, 2005), where the singleton cost was magnified under high WM load. This finding also contrasts with previous suggestions of a role for WM load in hearing (Dalton et al., 2009).

However, although the results of the probe analysis for both RTs and error rates strongly suggested for a successful manipulation of WM load, it remains possible that the lack of WM load modulation might have been because of a failure in increasing WM demands enough to enable a very challenging high WM load setting. Indeed, the previous work on auditory WM load (e.g. Dalton et al., 2009) used a memory set of six items under high load, compared with five items used in the present experiment. This possibility was investigated in the next experiment by adding a sixth digit to the memory set under high WM load.

Experiment 7

In order to increase the strength of the load manipulation in the present experiment, I added one extra digit to the high load memory set. In order to maintain a close perceptual match between high and low load conditions, a digit was also added to the low load set, but because in this condition all digits were presented in numerical order, the addition of one digit is unlikely to have increased the load substantially.

Method

Participants

18 new participants (three males) were recruited in exchange for course credits or a monetary reward. The average age was 19 (ranging from 18 to 20 years) and two (females) were left-handed.

Stimuli and Procedure

The stimuli were identical to the previous experiment, with the exception of the added digit to the memory set. The whole sequence now occupied 6° of visual angle. Again, the probe digit could reflect the identity of each position in the sequence with equal likelihood, apart from position 6 to which the probe digit never referred. The procedure was identical to that of Experiment 6.

Results and Discussion

Data from two participants were excluded as performance on the selective attention task was at chance level (> 50% errors): in the high WM load distractor absent condition for one participant and across all conditions for the other participant. This indicates that they were not able to successfully discriminate the target tone. For the remaining 16 participants, RTs slower than 2,500 ms were excluded from the analysis (1% of the trials).

Probe

Analysis of error rates demonstrated a significant increase in errors under high WM load (M = 28%) compared with low WM load (M = 3%), t(15) = 6.84, p < .001, d = 2.22. These results demonstrate a successful manipulation of WM load. Furthermore, RT analysis of performance on the memory probe revealed that responses were significantly slower under high WM load (M = 1446 ms) than under low WM load (M = 1193 ms; t(15) = 5.7, p < .001, d = 1.05, which is in line with the error rates (although the RT analysis is less reliable, as discussed in relation to Experiment 6).

RTs

Selective attention task. As in Experiment 6, trials with an incorrect response to the memory probe and incorrect trials on the selective attention task were excluded from the analysis. A 2 (WM load: low, high) × 2 (singleton: present, absent) repeated measures ANOVA revealed no main effect of load, F(1,15) < 1, η_p^2 = .003, suggesting that overall response speed on the selective attention task was not affected by the level of WM load in the secondary task. The main effect of singleton presence was significant, F(1,15) = 21.7, MSE = 5431.17, p < .001, η_p^2 = .591, with RTs slower in the presence of a singleton (M = 644 ms) compared with singleton absent trials (M = 559 ms). In line with Experiment 6, the WM load × singleton interaction was not significant, F(1,15) < 1, η_p^2 = .001, further suggesting that WM load does not modulate the extent to which a salient event captures attention in hearing (see Table 8).

As in Experiment 6, an additional 2 (WM load: low, high) × 2 (singleton position: before, after) repeated measures ANOVA was run. Neither the main effects of WM load (F(1,15) < 1, η_p^2 < .001) and distractor position (F(1,15) = 1.068, p = .318, η_p^2 < .066) nor the interaction were near significance (F(1,15) < 1, η_p^2 < .001), suggesting that distractor position did not affect task performance.

Table 8. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 7 as a function of WM load (low, high) and singleton presence. SDs are in brackets. Singleton cost (present – absent).

	WM Load					
	Low		High		Singleton cost	
	Present	Absent	Present	Absent	Low	High
Mean RT	649 (204)	561 (176)	640 (203)	556 (164)	88	84
% Errors	15 (.1)	9 (.06)	16 (.11)	9 (.07)	6	7

Error Rates

A 2 (WM load: low, high) × 2 (singleton: present, absent) repeated measures ANOVA was run on the error rates. As for the RTs, there was no significant main effect of load, F(1,15) < 1, $\eta_p^2 = .019$, while the main effect of singleton was significant, F(1,15) = 15.01, MSE = .004, p < .001, $\eta_p^2 = .500$. The presence of a singleton resulted in more errors (M = 15%) compared to singleton absent trials (M = 9%). Again, the load × congruency interaction failed to reach significance, F(1,15) < 1, $\eta_p^2 = .025$ (see Table 8).

In line with the RT analysis, an additional 2 (WM load: low, high) × 2 (singleton position: before, after) repeated measures ANOVA was run to determine whether the error rates differed depending on the singleton position in relation to the target position. The main effect of WM load was not significant, F(1,15) < 1, $\eta_p^2 = .030$, and neither was the main effect of distractor position, F(1,15) = 2.21, MSE = .012, p = .158, $\eta_p^2 = .128$. Furthermore, the interaction also failed to reach significance, F(1,15) = 3.15, MSE = .004, p =.096, $\eta_p^2 = .173$. Again, the results on the error data confirmed that the position of the singleton in relation to the target did not affect task performance.

Overall, as in Experiment 6, the presence (vs. the absence) of an irrelevant singleton distractor resulted in a performance cost on both RTs and error rates, which is in line with the findings of Dalton and Lavie (2004). As evident through both RTs and error rates, the load manipulation was effectively strengthened in the present experiment (mean effect = 253 ms; 25% errors) in contrast with that of Experiment 6 (mean effect = 207 ms; 11% errors). However, despite this increase in WM demands under high load, the singleton cost did not vary as a function of WM load. It is therefore unlikely that the results in the previous experiment – and indeed in the current experiment – might have occurred because the WM load manipulation was not effective enough. Instead, it seems that the magnitude of performance cost in the presence of a singleton distractor sound is not affected by the availability of WM capacity. These results do not support a general role of WM load in hearing, or at least not in a task set-up measuring auditory attention capture. Furthermore, the findings are not in line with the visual demonstration of differences in attentional capture depending on the WM load in the secondary task (Lavie & De Fockert, 2005; 2006).

Chapter Discussion

In this chapter, I sought to further investigate whether the principles of load theory would hold in hearing. Whereas Chapters 2 and 3 provided a thorough examination of auditory perceptual load, Chapter 4 focused on a more recent addition to the theory; namely WM load (e.g. Lavie et al., 2004). While the previous study used a response competition paradigm (Dalton et al., 2009), I attempted to extend the findings of a role of WM availability in auditory attention to an attentional capture task, where distractor interference is quantified through the cost on performance in the presence of a singleton tone compared to its absence. Thus, this singleton affects performance but given that it is completely irrelevant to the task it does not compete for a response which means that this type of task offers a pure measure of distractor processing rather than competition occurring at response level. In vision, it has been demonstrated that the same role of available WM capacity holds even when the distractor is entirely irrelevant to the task (e.g. Lavie & De Fockert, 2005; 2006), but to this date there has never been a similar investigation using an auditory task with completely irrelevant distractor sounds. Over two experiments I consistently failed to find any suggestion of increased performance cost as WM was loaded, which is contrary to the predictions of load theory, which suggest that distractor processing should increase as the executive control capacity is exhausted (in this instance through the retention of random digits). This finding remained despite the attempt in Experiment 7 to increase WM memory demands compared with Experiment 6. These results over the two experiments are not in line with the previous demonstration of a role of WM load in hearing (Dalton et al., 2009).

While Experiments 6 and 7 measured performance cost by comparing RTs (and errors) in singleton absent trials with those in singleton present trials, the previous study finding support for WM load used a response competition task (Dalton et al., 2009). More specifically, the elevation (high or low) of the target sound was either congruent or incongruent with the elevation of the distractor sound. Even though the distractor was irrelevant to the task at hand, it would still have competed with the target, firstly because it could appear in a position where the target could also appear (but not at the same time) and secondly because it shared the same elevation characteristic which was the defining feature of the target identity. Conversely, the two experiments reported in this chapter used a distractor sound that was completely irrelevant to the task. Although the distractor appeared within the same sequence as the target, it did not share any of the target defining features which arguably makes it much less relevant to the task at hand than the distractors used by Dalton et al. It therefore seems all the more likely that the influence of available WM resources on distractor processing seen by Dalton et al. might have been driven by WM involvement in resolving the response competition, which occurs at a late stage in processing. On the other hand, Experiments 6 and 7 were more likely to measure an earlier influence of WM load on auditory distractor processing, because the attentional capture task used in those experiments would not have led to response competition effects (e.g. De Fockert & Bremner, 2011). In this instance, no effect of WM load was apparent. It might therefore be the case that the influence of WM load on auditory distractor processing only holds in situations where WM is involved in resolving response competition at a late stage in processing. Future studies could attempt to further investigate this suggestion by examining the role of WM load on auditory distractor processing on a different task measuring response competition (for example one of the flanker tasks developed in Chapters 2 and 3). In those experiments, although the distractor shared a defining feature with the target (i.e. the same or opposite identity), it was always presented from a different spatial position from where the target could appear, making it less open to such strong response conflicts as in Dalton et al. This could potentially resolve the question of what role WM plays in auditory distractor processing. Findings in line with the present findings would suggest that, rather than determining the extent to which auditory distractor processing occurs in general, WM only has an effect when there is response competition arising between the target and distractor.

It has been argued (e.g. Lavie et al., 2004) that availability of WM capacity should matter exclusively when there is sufficient competition for selection between relevant and irrelevant stimuli, and this proposal has been confirmed in visual settings (e.g. Carmel et al., 2012; De Fockert & Bremner, 2011; Macdonald & Lavie, 2008). As there were strong costs associated with the presence of the singleton sound across both of the present experiments, this requirement was clearly met, however the predicted modulation of performance cost by WM load did not arise. This may have been due to the nature of the processing the singleton distractor sound engages. One might argue that the singleton is likely to capture attention through involuntary, bottom-up mechanisms, due to its comparative salience (as argued, for example, by Theeuwes (2004) in the case of visual attentional capture). In this case, loading WM might not affect the extent to which task focus can be maintained as the process of attentional capture is too involuntary and automatic to be resolved by top-down control – even when such processes are available (as is presumably the case under low WM load). According to this account, one reason for the discrepant results between the current findings and the visual findings demonstrating of a WM modulation on attentional capture (Lavie & De Fockert, 2005; 2006), could simply be that the singleton sound is comparatively more salient than the visual equivalent. However, note that a recent study failed to find an effect of WM load on attentional capture by a visual singleton distractor (De Fockert & Theeuwes, 2012). Performance costs in the presence (vs. absence) of a colour singleton were not significantly different between high and low WM load, in line with my findings. However, the presence of the distractor was perfectly predictable as it was blocked which may have reduced its comparative salience (as argued by De Fockert & Theeuwes). Despite this, there was a modulation revealed on distractor processing in the fMRI results, such that there was a positive correlation between the size of the performance cost under high WM load and activity in the inferior frontal gyrus. Thus, there was a suggestion of WM influence on task performance, despite this not being evident in the behavioural results. This suggests that with a more sensitive measure like fMRI it might be possible to demonstrate an effect of WM load on processing of auditory singleton distractors.

However, it is important to mention that a unique auditory singleton distractor is not always able to capture attention. For example, Dalton and Lavie (2007) found that the performance cost associated with the presence (vs. absence) of an irrelevant singleton distractor was diminished by changes in participants' attentional set in sequences that were otherwise very similar to those of Experiments 6 and 7. It thus seems that auditory attentional capture can be influenced by the processing strategies employed by participants, as even highly salient distractors can fail to capture attention under some circumstances. This finding makes it somewhat difficult to argue that auditory singleton stimuli are always processed in an involuntary fashion. Nevertheless, it remains possible that the auditory system is less open to modulations of distractor processing than the visual system, which might go some way towards explaining why the singleton was processed to the same extent here regardless of WM load in the concurrent task.

Load theory argues for a general role of the availability of WM resources in the ability to stay focused on the task and to ignore irrelevant distractors, which means its predictions should not be confined to any particular sensory modality. In other words, exhausting WM capacity with any kind of WM task should have the same detrimental effect when attempting to selectively focus in on relevant stimuli, even if the WM load and the attention task do not draw on the same type of mechanisms (e.g. verbal WM and a visual search task) which indeed has been demonstrated (e.g. De Fockert et al., 2001; Lavie & De Fockert, 2005; Rissman, Gazzaley, & D'Esposito, 2009). However, some findings contradict this suggestion by demonstrating that the type of WM engaged largely determines whether distractor processing increases under high (vs. low) WM load. For example, Kim, Kim and Chun (2005) investigated whether distractor interference on a Stroop task would differ depending on the type of WM task employed (either verbal or spatial). A Stroop task is a classic measure of distractor interference, and it commonly involves naming the colour a word is presented in (Stroop, 1935). When the meaning of the word is incompatible with the colour of the ink (e.g. the word 'red' written in blue ink), responses are typically slower than if the meaning is compatible with the ink, or if the semantic of the word is neutral (e.g. table). Kim et al. found that distractor interference on the dual task setting was larger than when the Stroop task was performed on its own, but only for the verbal WM task. Thus, the spatial WM task did not lead to greater Stroop interference than the single task condition. This dissociation between the two WM tasks suggests that the type of WM capacity engaged does play a role in whether distractor interference increases under high (vs. low) WM load. Similarly, another study (Park, Kim, & Chun, 2007) had the WM task overlapping with either the target or the distractor. Two stimuli – each consisting of a face image that was superimposed on a photograph of a house – were concurrently presented and the task was to memorise either the face or house images. Subsequently, two images were simultaneously presented, and participants made a same/different judgement on either the faces or the houses. A probe image was then presented, and participants determined whether the image was one of the two images memorised from the earlier memory set. Similarly to Kim et al., distractor interference was only larger when the type of images to memorise corresponded with the type of images attended to in the same/different judgement task.

Based on these findings, Park et al. (2007) suggested for an amendment of the existing load theory, which they coined the 'specialised load account'. Rather than arguing for a general WM capacity, they propose that there are individual mechanisms at play, each of which has their own limited capacity. Thus, the idea is that WM load only plays a role if the mechanism involved shares the same kind of processing as the attention task (e.g. both are verbal tasks). However, some evidence in line with load theory clearly has very little overlap between the type of WM load and selective attention task used, where for example increasing spatial WM load (e.g. spatial congruency task) lead to decreased processing of irrelevant information on a verbal task (e.g. flanker task with letters; De Fockert et al., 2010). Findings like this are difficult for the 'specialised load account' to reconcile.

Recently, support for the 'specialised load account' (Park et al., 2007) was reported in the auditory domain (Dittrich & Stahl, 2011). The congruency effect in a verbal auditory Stroop task (the word 'Man' or 'Frau' spoken in a male or a female voice) was greater when participants concurrently performed a high verbal WM load task compared with a no load condition. Interestingly, the distractor interference on the verbal Stroop task did not differ in the presence of a high nonverbal WM load task (memorise the duration of a sequence of tones), compared with the no load condition. This pattern of results was reversed for a nonverbal Stroop task (presentation of a high or low frequency tone at either a high or low-positioned speaker) as performance was worse during the high nonverbal WM load task but no different during the high verbal WM load task. This means that there was a double dissociation evident for the type of selective attention task and the WM load task used. Thus, the results strongly suggest that the amount of distractor interference depends not only on whether the dual task is of a high WM load, but also on what type of WM it consists of.

The convergence of evidence suggesting that the role of WM load in maintaining task priorities may not be as general as outlined by the load theory (e.g. Lavie et al., 2004) makes it possible that the failure in the present experiments to find any modulation by WM load of auditory singleton distractor processing may have occurred because the WM task did not share the same cognitive mechanism as the selective attention task. In Experiments 6 and 7, the selective attention task was of a nonverbal nature, while the WM load task was verbal, which means that they may have tapped into different cognitive control capacities. One interesting study would thus be to investigate whether using a nonverbal WM task with the present auditory capture task might display results following the prediction of load theory (e.g. Lavie et al.). However, it is important to note that the experiments demonstrating dissociations depending on whether the two tasks belong to the same categories (e.g. Dittrich & Stahl, 2011; Kim et al., 2005; Park et al., 2007) used a dual-task versus a single-task set-up, which cannot be directly comparable with a paradigm employing a high versus low WM load task. Although one could perhaps argue that a low WM load task is equivalent to a no-load task as no active rehearsal of the stimuli is needed in order to successfully perform the task, the low load task set-up nevertheless requires the coordination of two concurrent tasks, compared to a no load paradigm where only a single task is performed. In fact, Lavie et al. (Experiments 4 and 5; 2004) demonstrated that performing the memory task in full followed by the selective attention task resulted in greater distractor interference compared to when the selective attention task was performed on its own, suggesting that coordination of two tasks alone (even when performed in succession) is sufficient to reduce the cognitive control available for maintaining task priorities. Furthermore, this effect was no different whether the memory task consisted of memorising six digits or one digit. Although it is difficult to argue that the difference between a no load comparison and a low load comparison could explain the pattern of findings supporting the specialised load account, it would nevertheless be interesting to include a no-load condition as well as a low load condition to examine more directly the influences of the particular baseline task used.[1]

To conclude, the present chapter failed to find any support for the role of WM load in the ability to stay focused on an auditory task in the presence of an intrusive

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[1] In fact, I did pilot the material for this study using a nonverbal WM task consisting of a sequence of four tones of either high or low frequency which participants were informed to rehearse as they performed the same auditory attentional capture task. A probe then appeared asking the participants to indicate whether the tone in a specific position had been of high or low frequency. However, participants found it near impossible to perform the task as the stimuli simply were too similar in order to maintain task priority.

singleton distractor sound. These findings are in direct contrast with the predictions of load theory (Lavie et al., 2004). Although a few previous studies have demonstrated a WM load modulation on distractor processing in an auditory task measuring response competition (e.g. Dalton et al., 2009), it may be that in the auditory modality this influence is restricted to situations whereby a clear response conflict occurs at a late stage of processing, where availability of WM capacity is crucial in order to maintain task focus. As an entirely irrelevant distractor does not compete for a response, the influence of WM load (if any) must occur at an earlier stage in processing (as argued by De Fockert & Bremner, 2011). It could be that for auditory stimuli, WM load can only influence performance if the competition occurs at a late response level of processing. However, further experiments would be warranted to investigate this possibility. Regardless of whether this holds true, the two experiments reported in this chapter converge with Chapters 2 and 3 as they all demonstrate that the auditory system is not as open to modulations of distractor processing as is the visual system. As no within-participants effects of auditory distractor processing have emerged so far in this thesis, Chapter 5 moves on to consider potential differences between participants.

Chapter 5 – Individual Differences in Auditory Distractor Processing

Introduction

Chapters 2 and 3 investigated whether the perceptual load of a relevant task can affect the extent to which processing of irrelevant distractors occurs. Across five experiments reported over the two chapters, I failed to find any support for the idea that perceptual load would be a critical determinant for successful selection. Chapter 4 examined the role of WM availability on the performance cost that has repeatedly been reported to occur in the presence of an auditory singleton distractor (e.g. Dalton & Lavie, 2004). Chapter 4 failed to find any modulation by WM load of the magnitude of the singleton cost. Taken together, these results suggest that hearing is not as open to modulations of perceptual and WM load as is vision – a modality in which load theory has received a large amount of support. This is likely to reflect the fact that the mechanisms of attentional selection in hearing are different to those in vision. Whereas spatial selection in the visual system allows for strong focusing of processing capacity on a particular portion of the input, the selective process in hearing seems not to be as focused. As a consequence, it seems that auditory distractors are more likely to be processed regardless of the ongoing demands of the relevant task, because some spare capacity might remain available at all times.

This possibility raises other intriguing questions regarding the selective processes in the auditory domain. So far, I have consistently demonstrated that auditory distractor processing does not seem to be as open to modulations in the visual modality (at least within the framework of load theory). However, all studies so far have provided investigations on a group level, rather than accounting for whether differences in selective processes of auditory input may exist between individuals. This is an important question to ask, in particular since research into selective attention commonly overlooks individual differences on task performance, based on the assumption that all participants are equal in the ability to selectively focus their attention. An additional aspect of this particular question is also the need to establish whether laboratory tasks measuring distractor processing do relate at all to with distractibility in the real world, as laboratory tasks often consist of simple stimuli repeated over hundreds of trials whereas the outside world is far richer and not so repetitive in its inputs. For this reason, the aim of this chapter is to investigate whether differences between participants on distractibility outside the laboratory can modulate the extent to which auditory distractors interfere with laboratory performance on a relevant task.

Distractibility in everyday life can have important adverse effects on task performance, such as not being able to focus on your own conversation because the people sitting next to you are discussing an interesting topic. It can also have more serious consequences such as failing to spot a pedestrian crossing the road right in front of you as you get distracted by a breaking news report on the radio. The Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982) is a widely used measure of individual differences in everyday distractibility with 25 items describing common cognitive failures such as “Do you find you forget appointments?” and “Do you fail to listen to people’s names when you are meeting them?”. Participants indicate on a five point Likert scale (from 0 to 4) how frequently they have experienced each incidence during the past six months, with higher scores indicating a greater level of distractibility. It has been demonstrated that the score on the questionnaire remains constant over time, which strengthens the reliability of the measure (Broadbent et al., 1982). Scores on the questionnaire have also been linked with real life occurrences where distractibility is likely to have caused the incident. For example, it has been demonstrated that high scorers on the CFQ were more likely to have a history of causing traffic accidents (Larson & Merritt, 1991). A similar pattern has been found in a sample of electrical workers (Wallace & Vodanovich, 2003), which also demonstrated a positive correlation between the number of work accidents and CFQ score. Furthermore, a positive correlation has been demonstrated between CFQ score and the occurrence of lost computer work due to failure in remembering to save files (Jones & Martin, 2003).

The CFQ measure seems to relate to cognitive functioning in a range of different contexts, which makes it likely that overall the CFQ reflects a general characteristic such as executive control capacity. If this holds true, then the CFQ should also reflect performance on more controlled attention tasks which are assessing cognitive failures such as distractor processing, but are less directly related to the everyday examples on the questionnaire. Indeed, this relationship has been demonstrated in the visual modality on the ability to sustain attention on a repetitive task, known as the sustained attention to response test (SART; e.g. Manly, Robertson, Galloway, & Hawkins, 1999; Roberston, Manly, Andrade, Baddeley, & Yiend, 1997; Smilek, Carriere, & Cheyne, 2010). For example, Robertson et al. (1997) presented participants with a visual stream of single digits and the task was to make a button press response to all digit identities but one (which required response to be withheld). There was a positive correlation between CFQ score and the failure to withhold a response (as required by the task parameters), with higher scorers demonstrating a higher occurrence of false alarms than lower scorers. Furthermore, the relationship between CFQ score and performance on a selective attention task measuring distractor processing has recently been demonstrated. Using a visual perceptual load task, Forster and Lavie (2007) demonstrated that under low perceptual load, high CFQ scorers were more distracted (as shown by slower RTs) in the presence of an incongruent distractor (vs. a congruent distractor) compared with the low CFQ scorers. In line with this, there was also a positive correlation between CFQ score and RT, which thus implied that the level of everyday distractibility (as indicated by the CFQ score) was related to the magnitude of distractor processing in the task (under low perceptual load). However, this difference in distractor processing was eliminated under high perceptual load, suggesting that individual differences in distractibility only matters in tasks where not all capacity is needed for processing of the relevant task. This finding suggests that distractibility measured through a computer task can in some circumstances be related to behaviour in everyday life. Similarly, Tipper and Baylis (1987) have also demonstrated a positive correlation between CFQ score and laboratory task performance. More specifically, they found RTs in a word categorisation task to be slower for high CFQ scorers than for low scorers in the presence of a semantically related distractor word, in comparison to a distractor consisting of a random string of letters. In a second experiment where the irrelevant distractor became the relevant target on the following trial (i.e. measuring negative priming; Tipper, 1985), low scorers were significantly slower than the high scorers. In fact, only the low scorers demonstrated negative priming (i.e. slower responses when the distractor subsequently became the target), which suggests that they successfully inhibited the distractor whereas the high scorers processed the distractor.

While the previous studies investigated the relationship between the CFQ and the extent to which distractor interference occurs, a more recent study used a dual task paradigm to examine the relative role of everyday distractibility and cognitive load on performance on an antisaccade task (Berggren, Hutton, & Derakshan, 2011). Participants moved their eyes towards (prosaccade) or away (anitsaccade) from a target as quickly as possible at the same time as responding to auditory tones. For low cognitive load, the task was simply to indicate each time a tone appeared, while for high cognitive load the pitch of the tone was discriminated (i.e. low, intermediate or high). It was found that high scorers on the CFQ performed worse overall on the antisaccade task compared with low scorers. Interestingly however, although an increase in cognitive load also led to slower antisaccades, this detrimental effect was no different between high and low scorers on the CFQ. Thus, it seems that the two factors were independently having an effect on task performance, without affecting each other. However, the failure to find an interaction between cognitive load and CFQ may be due to the load manipulation used, which did not seem to reflect a modulation of working memory capacity but rather perceptual processes. In this case, the task is crossmodal with an auditory perceptual load manipulation on visual distractor processing. The findings could thus be argued to support the previous failures to find evidence of crossmodal perceptual load effects (e.g. Rees et al., 2001; Tellinghuisen & Novak, 2003). Note that this finding would be in line with my suggestion made in the General

Introduction that crossmodal effects might only be seen with a visual manipulation of perceptual load.

Given the findings suggesting a relationship between visual selective attention and everyday distractibility, it is important to note that there has to date not been a similar investigation into the relationship between auditory selective attention and scores on the CFQ. For this reason, the current chapter asks whether performance on an auditory selective attention task relates to participants' reported levels of everyday distractibility. This question is particularly interesting given that very few items on the questionnaire particularly refer to auditory distractibility (indeed, the only three items that do refer to audition are: #7. Do you fail to listen to people's names when you are meeting them?; #9. Do you fail to hear people speaking to you when you are doing something else?; #19. Do you daydream when you ought to be listening to something?). The three studies reported in this chapter therefore investigated whether CFQ score could predict the amount of distractor interference in three different auditory selective attention tasks. Experiment 8 used the same flanker task as was used in Chapter 3, because this task has been demonstrated to provide a reliable index of distractor processing. Experiment 9 used a slightly different version of the flanker task in which all sounds had a simultaneous onset (as in Chapter 2). Experiment 10 on the other hand used the same auditory attentional capture task as used in Chapter 4. A particular motivation for the choice of two types of tasks was the fact that they measure distractor interference in different ways. While the two flanker tasks rely on response competition, the attentional capture task does not because the singleton distractor does not share a target-defining feature. As illustrated in Chapter 4, this difference in the way in which the distractor interferes might indeed result in different findings.

Although the CFQ score overall can be assumed to reflect a general characteristic such as executive control capacity, the specific items on the scale refer to a whole range of different everyday errors which may be related to several different underlying cognitive processes. Therefore, it has been investigated whether the full scale contains any subscales that some items relate to more than other items. For example, Wallace, Kass and Stanny (2002) ran a factor analysis on the CFQ and identified four different subscales, namely Blunders, Distractibility, Memory and Names. This subscale has been used in various studies to enable a more focused measure of cognitive failures. For example, the relationship between the distractibility factor and visual distractor processing was investigated in an attentional capture paradigm (Kanai, Dong, Bahrami, & Rees, 2011). It was demonstrated that responses to the orientation of a line within a target shape (defined as a circle among diamond-shaped nontargets) were slower when one of the nontargets was of a unique colour, compared to when the target had that particular attribute. Crucially, the attentional capture effect was larger for participants scoring highly on the distractibility measure compared with low scorers, which confirmed the relationship between everyday distractibility as measured through the relevant items on the CFQ and performance on a common test on the ability to ignore distracting information. As this is the first test to date of whether distractibility on an auditory selective attention measure correlates with scores on the CFQ, I will use both the full scale and the distractibility factor in order to enable a more robust test of this question.

Experiment 8

Method

Participants

60 participants (7 males) were recruited at Royal Holloway in exchange for course credits or a monetary reward. The average age was 19, ranging from 18 to 30 years, and 8 (females) were left-handed.

Stimuli and Procedure

The apparatus used to design and to run the present experiment were identical to the previous experiments. Auditory stimuli were presented over speakers. The study used a sequential flanker task consisting of six centrally presented letter sounds delivered in a female voice, of which one was the target letter (G or T). The remaining letter sounds were X’s. A male voice distractor letter (G or T) was presented in the middle of the sequence, from either the left or the right speaker. The flanker task was similar to the task used for the low load condition in Experiment 4, with the exception that the distractor absent conditions were excluded.

The Cognitive Failures Questionnaire (Broadbent et al., 1982) was used to measure participants’ everyday life distractibility. For the CFQ analysis, the score on all 25 items was added up to obtain the CFQ score. Following Wallace et al. (2002), for the distractibility factor, the score on the following items was added up: 1, 2, 3, 4, 15, 19, 21, 22 and 25.

The procedure was as described for Experiment 4. Participants completed one practice block of 12 trials, followed by six experimental blocks with 64 trials in each. Subsequent to completion of the experiment, the CFQ was administered.

Results and Discussion

Four participants (all females) were excluded as average error rates (14, 15, 21, 24%) were more than 2 SDs above the group average (5%; SD 4%). An additional participant (female) was excluded as average RTs (990 ms) were more than 2 SDs above the group average (555 ms; SD 120 ms). RTs longer than 2000 ms (0.4% of total number of trials) were excluded from the analysis, and so were incorrect responses for the RT analysis.

For illustrative purposes, Table 9 presents performance in each distractor condition separately for high and low scorers on the CFQ based on a median split (median = 47, ranging from 17 – 72). However, because of the many negative consequences associated with the dichotomization of individual differences measures (e.g. Cohen, 1983; MacCallum, Zhang, Preacher & Rucker, 2002), the main analyses consisted of simple linear regressions rather than relying on the median split approach.

Table 9. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 8 of low and high scorers on the CFQ as a function of distractor congruency (congruent, incongruent). SDs are in brackets.

	Distractor Congruency			
	Congruent		Incongruent	
CFQ Group	RTs	% Errors	RTs	% Errors
Low CFQ	521 (89)	3 (2)	540 (91)	5 (3)
High CFQ	550 (98)	4 (3)	574 (107)	5 (3)

RTs

Auditory attentional capture task. A one-way repeated measures ANOVA on distractor congruency (congruent vs. incongruent) revealed a significant main effect, F(1, 54) = 48.61, MSE = 265.97, p < .001, η_p^2 = .474, with slower responses in the incongruent condition (M = 557 ms) than in the congruent condition (M = 536 ms).

CFQ and task performance. A simple linear regression analysis was carried out to investigate whether the CFQ score would predict distractor processing on the auditory flanker task. Distractor congruency effects were calculated separately for each participant by subtracting the average congruent RTs from the average incongruent RTs. CFQ score was not a successful predictor of congruency effects, β = .068, t < 1, accounting for only 0.5 % of the variance in distractor congruency (R^2 = .005, F(1,53) < 1; see Figure 3).

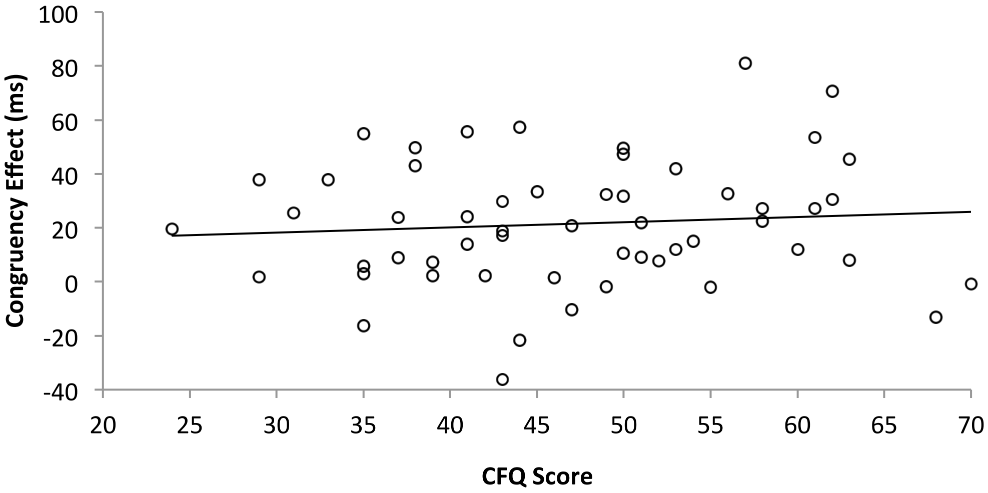

Figure 3. Simple regression for Experiment 8 displaying the relationship between CFQ score and congruency effect (incongruent distractor–congruent distractor) on the RTs.

Distractibility score and task performance. As this study specifically focused on distractor processing, a similar regression was run using scores on the distractibility factor (Wallace et al., 2002) as a predictor of distractor interference. Similarly to the overall CFQ analysis, distractibility score did not successfully predict distractor interference, $\beta = .030$, $t < 1$, accounting only for 0.1 % of the variance, $R^2 = .001$, $F(1,53) < 1$ (see Figure 4).

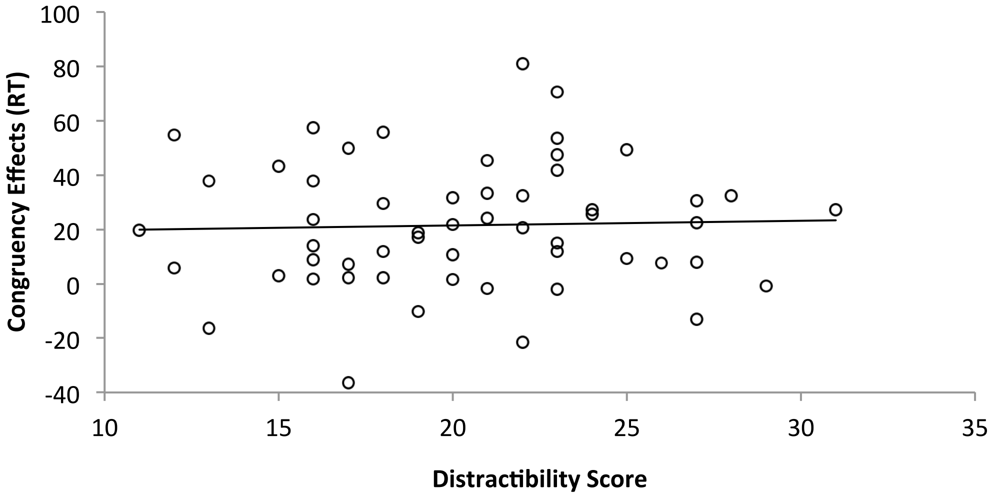

Figure 4. Simple regression for Experiment 8 displaying the relationship between distractibility score and congruency effect (incongruent distractor–congruent distractor) on the RTs.

Error Rates

Auditory flanker task. A one-way repeated measures ANOVA on distractor congruency (congruent vs. incongruent) revealed a significant main effect, $F(1, 54) = 22.87$, $Mse = .00028$, $p < .001$, $\eta_p^2 = .298$, with more errors in the incongruent condition ($M = 5\%$) compared with the congruent condition ($M = 4\%$).

CFQ and task performance. A linear regression analysis was carried out to investigate whether the CFQ score would predict distractor processing on the auditory flanker task. Distractor congruency was calculated by subtracting congruent error rates from incongruent error rates. CFQ score did not significantly predict congruency effects in the error rates, $\beta = .\text{-}215$, $t(54) = 1.6$, $p = .115$, explaining 4.6 % of the total variance ($R^2 = .046$, $F(1,53) = 2.57$, $p = .115$; see Figure 5).

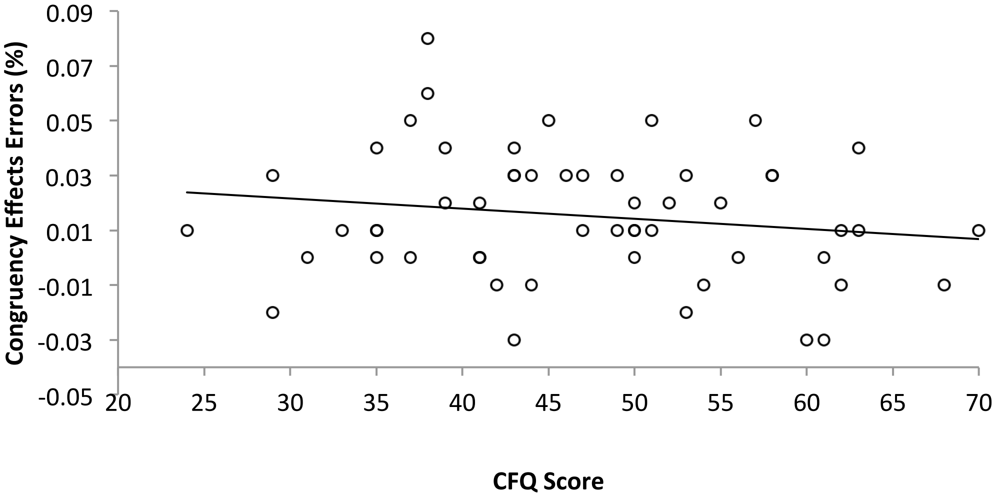

Figure 5. Simple regression for Experiment 8 displaying the relationship between CFQ score and congruency effect (incongruent distractor–congruent distractor) on the error rates.

Distractibility score and task performance. Similarly to the RT analysis, an additional regression was carried out on scores on the distractibility factor (Wallace et al., 2002) as a predictor of distractor interference in the error rates. In line with the RT analysis, the relationship between distractibility score and distractor congruency was not any stronger than that of the overall CFQ score, such that distractibility score did not successfully predict distractor interference, β = .-158, t(54) = 1.16, p = .25, accounting for 2.5% of the variance (R^2 = .025, F(1,53) = 1.35, p = .25; see Figure 6).

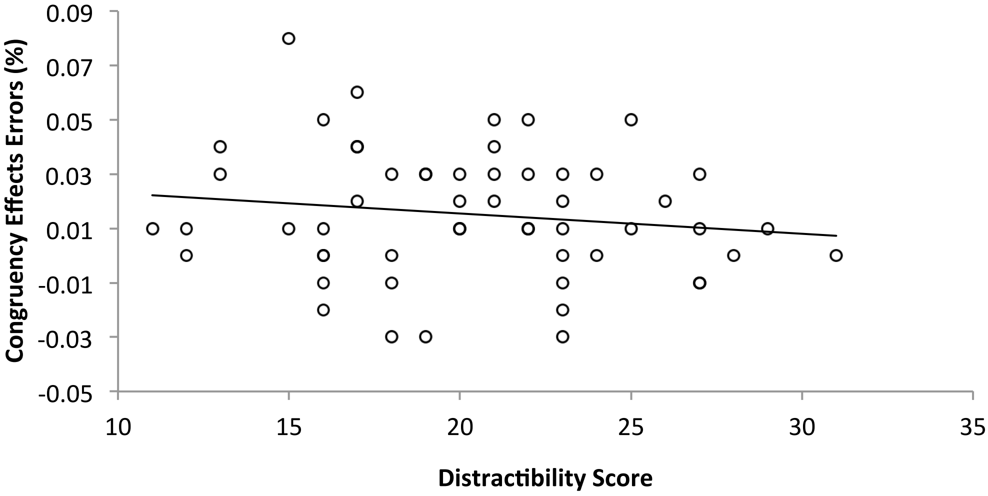

Figure 6. Simple regression for Experiment 8 displaying the relationship between distractibility score and congruency effect (incongruent distractor–congruent distractor) on the error rates.

Experiment 8 investigated the relationship between everyday distractibility as measured through self-report on the CFQ questionnaire (Broadbent et al., 1982) and distractor interference on an auditory flanker task. The performance on the flanker task showed marked distractor interference, such that responses were significantly slower and less accurate in the incongruent distractor condition compared with the congruent distractor condition. However, the degree of distractor interference did not relate to scores on the CFQ. Thus, while previous studies have found significant correlations between CFQ score and distractor interference in the visual modality (e.g. Forster & Lavie, 2007; Tipper & Baylis, 1987), the present experiment failed to extend these findings to the auditory domain. This was true even when specifically using the distractibility factor as a predictor of the congruency effect (Wallace et al., 2002).

The failure to find a relationship between performance on the auditory flanker task and score on the CFQ may have been related to the fact that the majority of items on the questionnaire do not relate to auditory processing. It is possible that the CFQ measure may relate more specifically to distractibility involving modalities other than hearing, such as vision, despite the demonstrations that the CFQ relates to everyday cognitive functioning in a range of different contexts (e.g. Jones & Martin, 2003; Larson & Merritt, 1991; Wallace & Vodanovich, 2003). In fact, differences between participants in performance on a selective attention task have been demonstrated to differ depending on the sensory modality involved in the task (Martens, Johnson, Bolle, & Borst, 2009). Participants performed a typical attentional blink task consisting of a rapid serial visual presentation (RSVP) stream of up to two targets and 16 to 18 distractors. A proportion of participants demonstrated little or no attentional blink (which occurs when the second target is presented in close temporal proximity from the first target and thus goes unnoticed; Raymond et al., 1992) compared with the remaining participants. However, this difference was eliminated when tested on an auditory equivalent to the visual task, as performance between the 'blinking' and 'nonblinking' participants was now equal. This remained even when the two tasks were closely matched for task difficulty. Thus, it could be possible that individual differences in distractor processing might not be as strong in the auditory domain as in the visual. Similarly to Martens et al. (2009), it would have been interesting to have provided participants with a visual flanker task as well as the auditory flanker task to compare whether a relationship may have been seen between CFQ score and the visual task. However, note that Martens et al. (2009) only identified a group of visual 'blinkers' and 'nonblinkers' and examined whether they would also show differences in an auditory task. Thus, they did not identify whether the visual 'nonblinkers' also were auditory 'nonblinkers'. It remains possible that different groups of people might be auditorily distractible and visually distractible. Thus, in relation to the lack of a link between individual differences in everyday distractibility and auditory distractor processing in the present study, it might be that a relationship would be seen using a questionnaire more focused on auditory distractibility in everyday life.

Since this was the first study to investigate the relationship between an everyday distractibility measure and distractor processing on an auditory selective attention task, it is difficult to draw any firm conclusions based on these findings alone. It was therefore important to determine whether the findings of Experiment 8 would replicate using a slightly different auditory flanker task.

Experiment 9

Experiment 9 used a similar task as designed in Chapter 2, which presented a target letter sound (X or N) centrally while a simultaneously presented distractor letter sound appeared from either the left or the right speaker. Whereas the distractor in Experiment 8 was either congruent or incongruent, the present experiment added a neutral distractor condition (i.e. the letter K). The previous versions of this specific task set-up either used a distractor absent condition (Experiment 1) or presented a congruent or incongruent distractor on all trials (Experiment 2). Although the distractor absent condition arguably provides a better baseline to contrast facilitation versus suppression of distractors, in this design the absent condition (under low load) means that the target is presented on its own, which runs the risk of introducing other presentational differences between the distractor absent condition and the two distractor present conditions. This potential issue was thus controlled for with the addition of the neutral distractor.

Although problems with the simultaneous presentation of sounds were highlighted in the discussion of Chapter 2, these were not as directly relevant to the current design because the number of items presented was always two (whereas in Experiment 1 they ranged from one sound to three sounds). Thus, no systematic differences in factors such as masking should occur between conditions.

The previous experiment investigated the relationship between everyday distractibility and performance on the laboratory task using both the CFQ score and the distractibility factor. However, since the results were no different, and since a focus on the distractibility factor rules out two of the three items that are most relevant to auditory contexts, the following experiments only used the total CFQ score as a measure of everyday distractibility.

Method

Participants

48 new participants (16 males) were recruited in exchange for course credits. The average age was 21, ranging from 18 to 34 years, and five were left-handed (three males, two females). One participant (male) was excluded as they reported non-normal hearing (cochlear implant).

Stimuli and Procedure

The apparatus used to design and to run the present experiment were identical to the previous experiments. The target letter (N or X, appearing with equal likelihood) was spoken in a female voice and always presented centrally. The distractor letter (N, X or K), presented in a male voice, was written to either to the left or the right speaker. The distractor letter was equally likely to be congruent, incongruent or neutral, and equally likely to be presented from either the left or the right speaker.

The procedure was similar to that of Experiment 8 with the following exception. Rather than administering the CFQ at the end of the experiment for all participants, half of the participants completed the questionnaire beforehand in order to avoid any potential order effects. Participants performed a practice block with 24 trials, followed by three experimental blocks with 48 trials in each.

Results and Discussion

Five participants were excluded from the analysis: one participant as average RTs (M = 1028 ms) were more than 2 SDs above the group mean (M = 699 ms; SD = 146 ms), one participant as average error rates (M = 42%) were more than 2 SDs above the mean error rates (M = 9%, SD = 10%), and a further three as performance in at least one experimental condition was at chance level (with error rates ≥ 50%). RTs longer than 2000 ms (0.6% of total number of trials) were excluded from the analysis, along with incorrect responses for the RT analysis. Although Experiments 8 and 10 used simple regressions for the main analyses, Experiment 9 used a regression to determine whether the CFQ score could predict distractor processing as well as a mixed ANOVA to further investigate the effect of adding the neutral condition to the flanker task, because the regression only considers distractor processing as a difference between the congruent and incongruent condition. To investigate whether performance on the flanker task changed as a function of level of distractibility, participants were divided in to a low scorer group and a high scorer group, using a median split (median = 47, SD = 13, ranging from 17 to 76). Table 10 presents performance in each distractor condition separately for high and low scorers on the CFQ.

Table 10. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 9 of low and high scorers on the CFQ as a function of distractor congruency (congruent, neutral, incongruent).

	Distractor Congruency					
	Congruent		Neutral		Incongruent	
CFQ Group	RTs	% Errors	RTs	% Errors	RTs	% Errors
Low CFQ	636 (128)	4 (4)	719 (168)	6 (6)	730 (159)	12 (10)
High CFQ	657 (125)	3 (5)	704 (168)	6 (9)	707 (137)	10 (11)

RTs

A mixed ANOVA with the between-subjects factor of scorer group (high, low) and the within-subjects factor of distractor congruency (congruent, neutral, incongruent) revealed no significant main effect of scorer group, F(1,40) < 1, , η_p^2 = < .001. There was a main effect of congruency, F(2, 80) = 27.6, MSE = 2406.68, p < .001, , η_p^2 = .408. RTs were significantly slower in the presence of an incongruent distractor (M = 718 ms) compared with a congruent distractor (M = 647 ms; t(41) = 6.54, p < .001, d = .519), but not in comparison with a neutral distractor (M = 711 ms; t(41) < 1, d = .04). The distractor neutral condition was significantly slower than the congruent condition, t(41) = 5.51, p < .001, d = .434. However, the interaction between congruency and scorer group failed to reach significance, F(2,80) = 2.28, MSE = 2406.68, p = .109, , η_p^2 = .054, which suggests that level of distractor processing did not differ depending on whether the participants belonged to the high or the low scorer group.

Similarly to Experiment 8, a linear regression was also carried out to investigate whether score on the CFQ would predict distractor processing in the flanker task. Again, the congruency score was calculated by subtracting congruent RTs from incongruent RTs. CFQ score did not reliably predict congruency effects on the auditory flanker task, β = .051, t <1, accounting only for 0.3% of the total variance for the congruency effect, R^2 = .003, F(1,40) < 1 (see Figure 7).

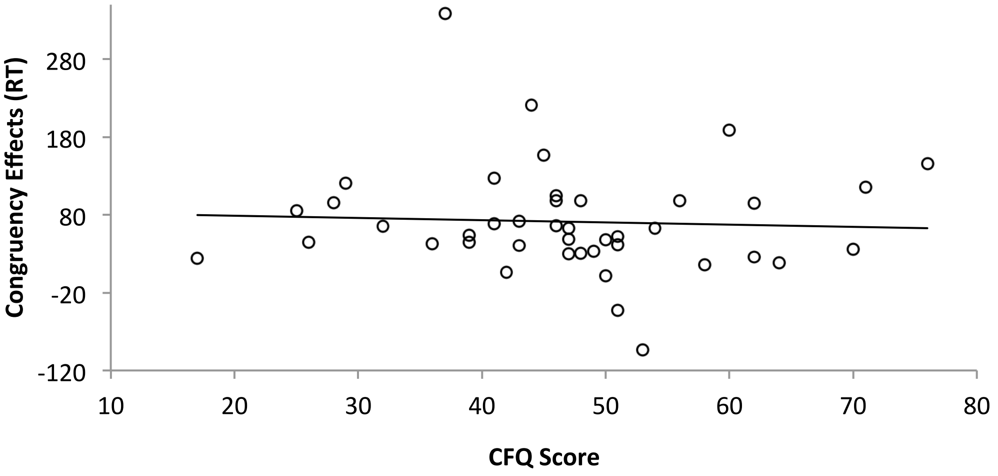

Figure 7. Simple regression for Experiment 9 displaying the relationship between CFQ score and congruency effect (incongruent distractor–congruent distractor) on the RTs.

Error Rates

Similarly to the RT analysis, a mixed ANOVA was carried out on the error rates with the between-subjects factor of scorer group (high, low) and the within-subjects factor of distractor congruency (congruent, neutral, incongruent). In line with the RTs, there was no effect of scorer group on the error rates, F(1,40) < 1, η_p^2 = .010. There was a main effect of congruency revealed, F(2,80) = 18, MSE = .004, p < .001, η_p^2 = .310, such that error rates in the incongruent condition (M = 11%) were larger than in the congruent condition (M = 3%, t(41) = 4.88, p < .001, d = .944) and than in the neutral condition (M = 6%, t(41) = 3.91, p < .001, d = .548. Furthermore, more errors were made in the presence of a neutral distractor compared with a congruent distractor, t(41) = 2.94, p < .005, d = .433. However, there was no significant interaction between CFQ group and distractor congruency, F(2,80) < 1, $\eta_p^2 = .002$.

A simple linear regression was also carried out with CFQ score as a predictor on the congruency effect in the error rates, which again was calculated by subtracting congruent error rates from incongruent error rates. In line with the regression carried out on the RT data, CFQ score did not significantly predict congruency effects in the error data, β = .020, t < 1, accounting for < 0.1 % of the variance, $R^2 = .0004$, F(1,40) < 1, (see Figure 8).

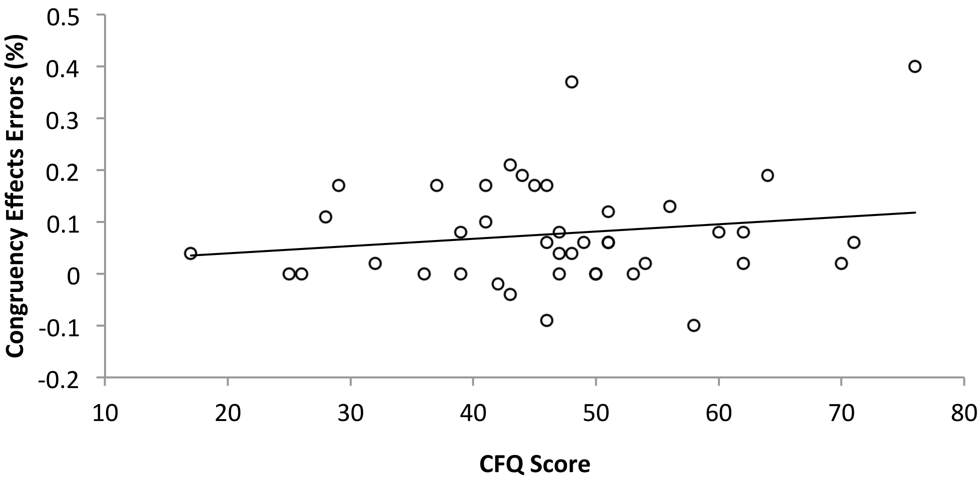

Figure 8. Simple regression for Experiment 9 with CFQ score predicting the congruency effect (incongruent–congruent distractor) in the error rates.

The aim of Experiment 9 was to investigate whether the findings of Experiment 8 would hold using a slightly different auditory flanker task. Rather than using a sequential presentation of the sounds, the target and distractor sounds were presented simultaneously. The present experiment also included a neutral distractor condition to allow for disambiguation between distractor interference and facilitation effects. Evidence was found both for interference due to incongruent (vs. neutral) distractors (error rates only) and for facilitation due to congruent (vs. neutral) distractors (RTs and error rates). However, performance on the flanker task did not vary as a function of CFQ group. Furthermore, in line with Experiment 8, the CFQ did not successfully predict the extent to which distractor interference impeded on task performance. This strengthens the findings from Experiment 8 to suggest that processing of auditory distractors in the laboratory flanker task used in these experiments does not relate to individual differences in people's reported distractibility in everyday life.

However, before making firm conclusions it was important to investigate whether a different measure of distractor processing would result in the same outcome. Thus, Experiment 10 used the same auditory attentional capture task as described in Chapter 4. Rather than presenting a distractor which could be of either the same or opposite identity as the target sounds, and therefore was somewhat relevant to the task, Experiment 10 presented entirely irrelevant singleton distractors which did not share any target defining features. As Chapter 4 strongly suggested that modulation of distractor processing by WM availability seems to depend on the type of task paradigm used, this was an added motivation for the following experiment.

Experiment 10

Experiment 10 provided a definitive test of whether everyday distractibility score can predict performance on an auditory selective attention task. Thus the aim of the experiment was the same as the previous two experiments of this chapter, measuring performance on an auditory attentional capture task (Dalton & Lavie, 2004).

Method

Participants

57 participants (11 males) of whom three were left-handed (one male) were recruited at Royal Holloway in exchange for course credits. The age of nine

participants (one male) was not documented due to error in recording. The average age of the remaining subset of 46 participants was 20, ranging from 18 to 27 years.

Stimuli and Procedure

The apparatus used to design and run the present experiment was identical to the previous experiments, and stimuli were presented over speakers at an average level of approximately 70 dB SPL. The experiment used a sequential presentation of five tones. The frequency of the target and nontarget tones was 440 Hz, while the singleton tone was presented with a frequency of 520 Hz. The duration of the nontarget and singleton tone were 100 ms, while the target was either 50 or 150 ms. The task was similar to the task used in Experiment 6 and 7.

Participants were asked to identify the duration of the target and they were also informed that there might be an odd sound appearing at a different frequency from the rest of the tones, and that failure to ignore it could potentially impede on task performance. At the start of each trial, the word “Ready” appeared at the centre of the screen for 500 ms. Subsequently, the sequence of five tones was presented. Directly following the sequence, a question mark appeared for 500 ms. Half of the participants indicated whether the target tone was shorter or longer by pressing the 1 or 2 key with the index finger and the middle finger of their right hand on the numeric keyboard respectively, while the inverse response pattern was used for the other half. Following the response, or if no response had occurred within 3000 ms, visual feedback appeared on the screen for 1500 ms. Participants performed a practice block of 24 trials, followed by 3 experimental blocks with 48 trials in each block. As in Experiment 9, the CFQ questionnaire was administered before the experiment for half of the participants, while the other half completed it after the experiment to avoid any potential order effects.

Results and Discussion

A total of nine participants were excluded from the analysis. Two participants failed to complete the full questionnaire. Four participants were excluded as performance in at least one experimental condition was at chance (with error rates ≥ 50%), indicating that they were unable to successfully discriminate the target. A further three participants were excluded as average RTs (M = 620 ms; 678 ms; 772 ms) were more than 2 SDs above the group mean (M = 358 ms; SD = 123 ms). For the remaining participants, mean RTs and accuracy were calculated as a function of singleton condition (present vs. absent). For illustrative purposes, Table 11 presents performance in each condition split between high and low scorers on the CFQ, based on a median split (median = 48, ranging from 17 to 72).

Table 11. Mean correct reaction times (milliseconds) and error rates for Experiment 10 of low and high scorers on the CFQ as a function of singleton condition (absent, present). SDs are in brackets.

	Singleton Condition			
	Absent		Present	
CFQ Group	RTs	% Errors	RTs	% Errors
Low CFQ	321 (86)	13 (10)	372 (104)	20 (11)
High CFQ	284 (53)	14 (9)	345 (83)	24 (10)

RTs

Auditory attentional capture task. A one-way repeated measures ANOVA on singleton condition (present vs. absent) revealed a significant main effect, F(1, 47) = 56.41, MSE = 1367.11, p < .001, η_p^2 = .546, with slower responses when the singleton was present (M = 358 ms) than when it was absent (M = 301 ms). The performance cost present provides further support for the suggestion that a unique, salient event is difficult to ignore even when completely irrelevant to the task at hand (e.g. Dalton & Lavie, 2004).

CFQ and task performance. A simple linear regression analysis was carried out to investigate whether CFQ score would predict performance cost on the attentional capture task. Cost was calculated for each participant by subtracting the average singleton absent RT from the average singleton present RT. CFQ score did not successfully predict reaction time costs on the auditory attentional capture task, β =

.127, t < 1, accounting for only 1.6% of the variance, $R^2 = .016$, F(1,46) < 1, (see Figure 9).

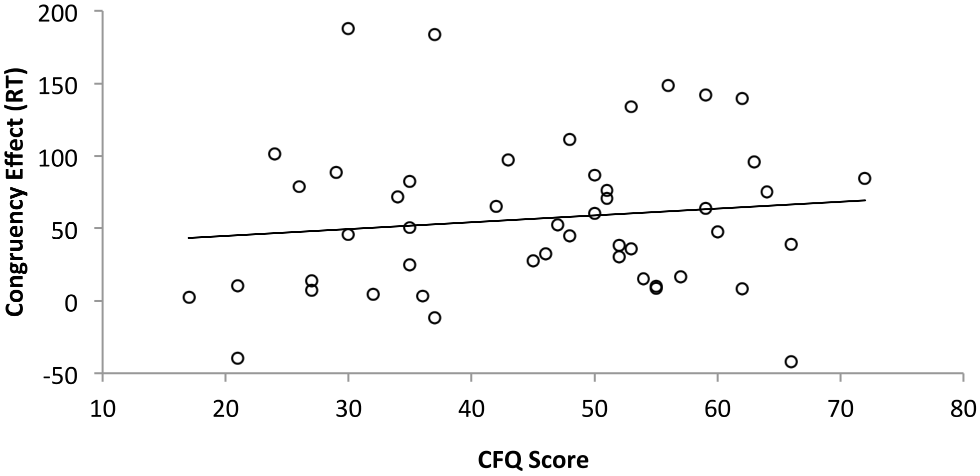

Figure 9. Simple regression for Experiment 10 displaying the relationship between CFQ score and performance cost (singleton present–singleton absent) in the RTs.

Error Rates

Auditory attentional capture task. A one-way repeated measures ANOVA with the factor of singleton condition (present vs. absent) revealed a significant effect, F(1,47) = 54.95, MSE = .004, $p < .001$, $\eta_p^2 = .539$. In line with the RT analysis, performance was worse in the presence of a singleton distractor, producing more errors (M = 28%) compared with its absence (M = 13%).

CFQ and task performance. A simple linear regression was carried out to investigate the relationship between CFQ score and performance cost on the error rates. Cost was again calculated by subtracting singleton absent errors from singleton present errors. Unlike the RT results, CFQ score was a significant predictor of performance, β = .306, t(47) = 2.18, $p < .05$, accounting for 9.3% of total variance ($R^2 = .093$, F(1,46) = 4.74, $p < .05$). Thus, there was a significant relationship between CFQ score and susceptibility to auditory attentional capture, such that participants with higher CFQ scores suffered more interference from irrelevant distractor singletons (see Figure 10). The means shown in Table 11 suggest that the increased singleton cost exhibited by the high CFQ scorers relates to higher error rates in the presence of the singleton which would be expected if these participants were genuinely exhibiting higher distractibility rather than reduced error rates in the absence of the singleton (which would have been a possibility given the use of a difference cost but harder to explain in terms of distractibility).

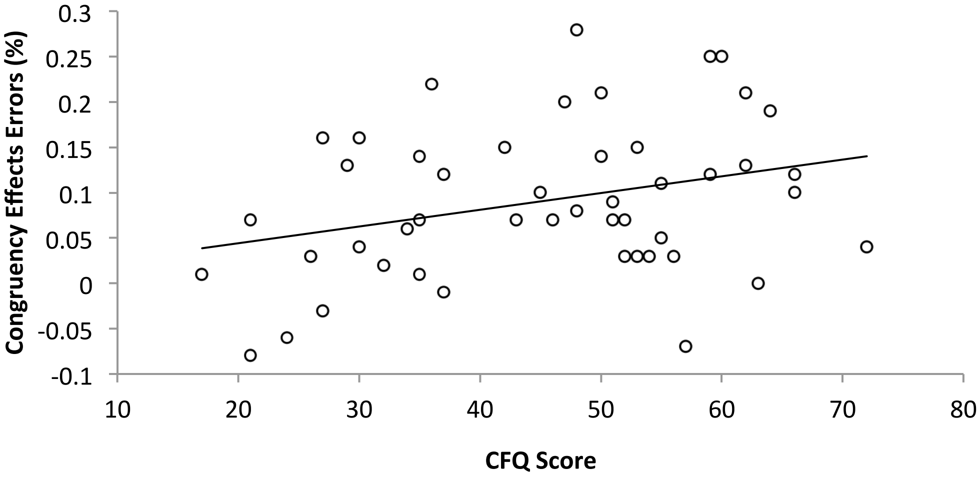

Figure 10. Simple regression for Experiment 10 displaying the relationship between CFQ score and performance cost (singleton present–singleton absent) in the error rates.

Experiment 10 sought to investigate whether a lack of relationship between reported everyday distractibility and performance on an auditory selective attention task which was demonstrated in Experiment 8 and 9 would still hold with a different measure of distractor processing. The present experiment thus employed an auditory attentional capture task, in which the distractor was entirely irrelevant to the task at hand. In clear contrast to the previous two experiments, there was a relationship demonstrated between CFQ score and performance cost in the presence of an irrelevant distractor. More specifically, the CFQ score successfully predicted the proportion of errors such that the higher score on the CFQ, the more errors were made during distractor present trials. This finding is the first to date to demonstrate a relationship between reported everyday distractibility as measured through the CFQ questionnaire (Broadbent et al., 1982) and performance on an auditory selective attention task. The findings are in line with previous findings demonstrating a relationship between a controlled laboratory task and everyday cognitive failures (e.g. Forster & Lavie, 2007; Ishigami & Klein, 2009; Tipper & Baylis, 1987), which ultimately strengthens the validity of the questionnaire and also demonstrates that a simple computer-based task indeed can relate to everyday behaviour. However the results are also in contrast with the previous experiments in this chapter, raising the question of why this relationship was observed in the attentional capture task used here but not in the flanker tasks used in Experiments 8 and 9. This issue will be addressed in the following section.

Chapter Discussion

The previous experimental chapters reported in this thesis have consistently failed to demonstrate any modulation of auditory selective attention, within the framework of load theory (e.g. Lavie, 1995; Lavie et al., 2004). The convergence of these results has led to the conclusion that auditory selective attention seems to be less open to modulations than is vision (at least in relation to load theory). However, these findings are only concerned with overall group performance. It was therefore of importance to investigate between-participant variability, and the particular focus of this investigation in the current thesis concerned whether or not variability in laboratory-based auditory distraction relates to reported distractibility occurring outside the laboratory.

The three experiments reported in this chapter used the CFQ (Broadbent et al., 1982) as a measure of everyday distractibility between participants. Furthermore, Experiment 8 also used the specific distractibility factor derived from Wallace et al. (2002), which uses a subset of the items in the CFQ questionnaire. Experiments 8 and 9 measured auditory distractor processing through response competition on a flanker task, while Experiment 10 employed an attentional capture paradigm using performance cost in the presence (vs. absence) of an entirely irrelevant distractor sound as a marker of distractor processing. Experiments 8 and 9 found no relationship between reported everyday distractibility and distractor processing, which is in direct contrast to previous successful reports (e.g. Forster & Lavie, 2007;

Tipper & Baylis, 1987). However, the findings from Experiment 10 were in direct contrast, such that a significant relationship between CFQ score and performance cost in the presence (vs. absence) of a singleton distractor was demonstrated in the error rates. More specifically, the higher the scores on the CFQ, the more errors were made during the distractor present condition, which suggests that the extent to which the irrelevant singleton impeded on performance related to the degree of reported everyday cognitive failures. This finding is in line with previous demonstrations in the visual modality of a relationship between the CFQ and a controlled laboratory task on selective attention (e.g. Forster & Lavie; Tipper & Baylis), and it is the first study to date to report such a relationship on an auditory selective attention task.

This finding is also of importance as it suggests that the auditory attentional capture task designed by Dalton and Lavie (2004) indeed relates to real life behaviour, despite being far removed from the common types of everyday behaviour people typically are engaged with (e.g. due to the repetitiveness of the task, the sparseness of the sounds presented and the artificial nature of the responses required). It is also important to note that the relationship between CFQ score and performance on a laboratory task can be generalised to a different sensory modality. This might suggest that what the CFQ measures relate to general executive control functions rather than functions only specific to vision (as all previous relationships between the CFQ and laboratory tasks have involved visual studies). This claim is strengthened by the fact that only three out of 25 items on the questionnaire are directly related to auditory processing, demonstrating that the CFQ can predict attention performance even on tasks that are markedly different from the particular instances of cognitive slips referred to in the questionnaire.

Although the results of Experiment 10 are in line with previous visual research, it is interesting to note that while a significant relationship was seen in the error rates and not the RTs, some previous studies have found a positive correlation in the RTs (e.g. Forster & Lavie, 2007; Kanai et al., 2011; Tipper & Baylis, 1987; although note that the latter two articles did not report correlation analyses for the error rates). It is likely that the response measure with which CFQ score is most likely to correlate might be determined by the specific parameters of the task. For example, it is possible that the unique singleton distractor used in Experiment 10 is particularly salient and might thus distract participants to a greater extent than a visual equivalent (as used by Kanai et al.) or a visual distractor sharing a response-related feature with the target (as used by Forster & Lavie, and Tipper & Baylis). Thus, the presence of the highly salient singleton might not only have resulted in a slowing in responses (which was equivalent between participants) but also have led to errors of commission. Most importantly, the errors of commission were particularly prevalent for participants reporting to be more prone to everyday distraction. It seems reasonable to suggest that the ultimate consequence of a distracting event would be an erroneous response rather than simply a slowing in response, which furthermore implies that variation in error rates might be more strongly related to cognitive slips occurring in everyday life compared with individual differences observed in RT interference.

This proposal might also explain why the relationship between CFQ score and auditory distraction were observed in the attentional capture task (Experiment 10) but not in the flanker task (Experiments 8 and 9). Error rates were substantially higher in the attentional capture task (28% in the singleton present condition) compared with both flanker tasks (5% in the incongruent distractor condition of Experiment 8 and 11% in the comparable condition of Experiment 9). Thus it may have been the case the error rates were simply not large enough in the flanker task to allow a relationship between distractor cost and CFQ score to become apparent.

Although Experiment 10 provides the first evidence to date to relate individual differences in auditory distractor processing to a measure of everyday distractibility, there have been other studies investigating individual differences in processing of irrelevant sounds. For example, Conway et al (2001) found that low WM span participants were more likely to process their own name in the unattended stream of sounds than were participants with a high WM span, suggesting that the latter group were more able to remain focused on the attended, relevant stream. An interesting future follow-up study would be to investigate the role of WM capacity on auditory distractor processing linked with the CFQ to examine whether a high WM span would correlate with a lower score on the CFQ and less distractor interference. This would be interesting in light of the suggestion I made in the Introduction Chapter that differences in CFQ might indeed relate to individual differences in WM capacity. It would also be interesting to investigate whether the findings demonstrated by Conway et al. (2001) would replicate with a slightly less meaningful distractor than the participants' own name, yet highly salient, such as the singleton distractor sound used in Experiment 10.

The findings demonstrating a relationship between laboratory-based auditory distractibility and CFQ score are important in light of previous studies reported so far in this thesis, which have consistently failed to find a modulation of auditory distractor processing as a function of both perceptual and WM load. The present findings suggest that although auditory distractor processing appears to remain relatively constant for each participant across varying task demands, there is nevertheless significant variation between participants in the extent to which irrelevant sounds tend to interfere with task performance.

While all experiments reported so far have used behavioural measures to investigate determinants of auditory selective attention, the final experimental chapter will provide an investigation using EEG to more closely examine the strength of attentional selection. More specifically, the final experimental chapter will investigate whether the value of a monetary reward linked with task performance can influence the selection of a target presented with a competing nontarget.

Chapter 6 – The Influence of a Monetary Reward on Auditory Selective Attention

Introduction

So far in this thesis, I have presented behavioural experiments investigating different determinants of auditory selective attention both within and between participants. Although these behavioural experiments can inform us about important aspects of cognitive functioning, these measures are limited in how much they can reveal as they measure performance linked to a physical action such as pressing a button in response to a target, making it hard to determine precisely at what stage in cognitive processing a difference between the conditions of interest actually occurs. Conversely, the EEG recording technique allows for a more sensitive measure of the timings of attentional selection, which typically occur earlier than the actual time a response is executed. This technique is thus favourable when assessing potentially subtle differences in the effects of selective attention across conditions. This chapter therefore expands on the previous experiments by not only investigating behavioural performance but also electrophysiological activity through the recording of EEG. While previous chapters have focused on the influence of perceptual and working memory load on auditory selective attention (Chapters 2–4) and the link between performance on laboratory tasks and everyday distractibility (Chapter 5), this chapter investigated the influence of a strong top-down control stemming from anticipated monetary reward on attentional selection to a relevant sound. Since the experiments reported so far have failed to demonstrate a modulation of auditory attentional selection by perceptual or WM load, it was important to investigate whether the strong top-down influence of target-associated reward might be able to modulate task performance.

There are certain situations and factors in our everyday life that may exert a particularly strong motivation for a successful search of a target, for example when looking for a friend in a crowded space or listening out for a special announcement at a noisy train station. These examples of attentional influences are likely to affect visual perception. In a review by Vuilleumier and Driver (2007), it was argued that not only does attention affect visual processing, such as through the strong top-down control highlighted in the examples above, but emotional and motivational mechanisms can also influence visual processing. These two mechanisms were argued to perhaps reflect separate (albeit connected) circuits in the brain which would both influence areas such as the visual cortex, and the outcome of such influence from both mechanisms would be very similar, such as improved responses to relevant stimuli. Arguably, one of the strongest motivations for enhanced processing of relevant stimuli may be that of monetary rewards, as there is a strong incentive for successful selection. However, the effect of monetary reward is also likely to directly influence attention, rather than simply influencing visual processing, due to the strong motivational aspect associated with a reward resulting in greater top-down control of attention.

In fact, evidence for an influence of reward on selective attention has previously been reported. For example, Della Libera and Chelazzi (2006) measured the amount of negative priming in a task using Navon figures (Navon, 1977); in this case a numerical prime figure (e.g. number five; global figure) comprised of smaller figures (e.g. number six; local figure). The local figures were either congruent or incongruent with the global figure. Prior to each trial, a cue indicated whether participants should respond to the local or the global pattern of the prime figure. Participants were randomly allocated a high or a low reward following a correct response. A probe figure then appeared which was either the global letter X comprised of local numbers or a global number with local Xs, and participants made a response to the number featured in the figure. Importantly, there were only reliable negative priming effects to the probe feature following a high reward trial, while responses to stimuli associated with selection on a lower reward trial did not induce negative priming. This finding suggests that inhibition of responding to the distractor lasted on to the probe task after a highly rewarded trial, while this inhibition was quickly eliminated under low reward due to the less favourable outcome. In a similar study (Della Libera & Chelazzi, 2009), a final delayed session was added whereby the reward component was removed. Interestingly, stimuli in the final session which had been associated with a high reward during the learning sessions were now more quickly detected and created larger negative priming when acting as distractors, compared with stimuli associated with a lower reward which showed the opposite pattern – despite the lack of a reward aspect to the experiment. Taken together, these studies clearly demonstrate that reward can influence attention to optimise ‘more favourable’ processing which has a durable effect.

While the previous experiments investigated the effect of reward through negative priming which largely measures distractor inhibition, other studies have more directly measured target processing. For example, in a study by Raymond and O’Brien (2009) participants learned to associate a reward or punishment (high or low) with particular faces, which were subsequently used as stimuli in an attentional blink task. Even though the attentional blink task did not include any reward or punishment values, the rate of recognition of the faces depended on the previous value of each face. More specifically, the faces associated with a high reward were more accurately detected whereas the faces associated with a lower reward or no reward showed an effect of attentional blink, suggesting that the value of the face influenced whether attention was focused on it or not. Altogether, these results further suggest that the learned motivation to readily respond to a stimulus due to its associated reward value persists even when participants are aware that such task parameters no longer apply, illustrating the strong influence reward can have on selective attention performance.

The effect of associated reward on target selection has further been illustrated in a number of studies measuring attentional capture on a visual search task (Anderson, Laurent & Yantis, 2011a; 2011b; 2012). All studies involved a practice phase whereby participants identified the orientation of a bar within a target shape defined by colour, presented in a circle amongst colourful nontargets. Reward for accurate performance on each trial could be either high or low, depending on the colour of the target (one of two different colours). In the test phase, the reward aspect was no longer present, and the target was now defined by shape rather than colour. In one study (2011a), all nontargets were of different colours, of which one consisted of one of the previous target colours. Interestingly, even though this nontarget was surrounded by other colourful nontargets, it captured attention nevertheless which was evident though slower responses to the target shape when it was present compared to when it was absent. Furthermore, it was also demonstrated that reward could influence the extent to which a salient nontarget captured attention (2011b). This study was similar to the previous experiment, but in this instance the nontarget of the same colour as the previous target was surrounded by black nontargets, which increased its salience. Although both colours (which had previously been associated with reward) did capture attention, the capture effect was stronger for the colour which was associated with a high reward compared with the low reward colour. Thus, the findings demonstrate that reward can influence processing of a salient stimulus which largely proceeds in an involuntary fashion, suggesting that reward seems to play a similar role as physical saliency in attentional control, given that the most salient stimulus should have been the unique target shape. Indeed, it has been suggested that enhanced selection to reward-related stimuli reflects an automatic mechanism which proceeds independently from top-down and bottom-up influences on attention (e.g. Anderson, 2013).

Although the aforementioned studies have provided strong evidence for an influential role of reward on selective attention through behavioural measures, they cannot directly inform how the time course of attention is affected by reward. Recently, there has been evidence reported for differences in amplitude and onset for ERP components as a function of reward. Kiss et al. (2009) recorded EEG during a visual search task to more closely investigate the effect of reward on attentional selection. A red or green target appeared among grey nontargets, presented in a circle display. All stimuli were diamond-shaped with a notch either at the top or at the bottom. The task was to determine the location of the notch on the target. Prior to each block, participants were informed that fast and accurate responses to either the red or the green target could result in 5 bonus points, while responses towards the other target colour could lead to a lower reward of 1 bonus point. The colour and reward association changed between blocks. The N2pc component was used to investigate any differences in timing and magnitude of selection to the target. The N2pc is an ERP component which is associated with focusing of attention towards the target in a set of competing stimuli and it is therefore a suitable measure of the time course of attentional selection (e.g. Luck & Hillyard, 1994a; 1994b). The N2pc is associated with a greater negative voltage observed around 200–300 ms after target onset at the posterior areas in the hemisphere contralateral to the spatial location of the target (e.g. on the left hemisphere for a target positioned to the right) compared to the ipsilateral hemisphere. It is identified by subtracting the contralateral waveforms from the ipsilateral waveforms, creating a difference wave. Due to the laterality of the N2pc, the target only appeared in the positions on the left or the right hand side of the circle (and not at the top or bottom positions). Behavioural performance was improved when participants made judgements on the high reward target, compared with the low reward target colour. This was accompanied by an earlier and larger magnitude of the N2pc. Thus, the findings strongly indicated that attentional selection occurred at an earlier time point through the influence of the reward aspect the target colour was associated with, even though the actual task was not related to target colour.

Another strong influence of reward on task performance measured through the N2pc component was recently reported by Hickey et al. (2010). Similarly to Kiss et al. (2009), participants judged the orientation of the line within a target shape which was different in colour and shape from the uniform nontargets. On some trials, one of the nontargets was of a different colour, making it a singleton distractor. The colour of the target and the singleton (if present) changed between trials such that the colour of the target on some trials was the colour of the distractor on other trials. Rather than explicitly linking reward (high vs. low) with a target feature as in Kiss et al.'s (2009) study, reward was randomly allocated after each trial. This (similarly to Anderson et al., 2011b) allowed for a closer investigation into whether an effect of reward simply reflects an increase in top-down strategy and motivation or if the reward association occurs automatically and is dissociable from strategy and bottom-up stimulus saliency. The behavioural results demonstrated faster responses when the target colour associated with high reward remained the target on the following trial compared to when it swapped to become the distractor colour, despite colour being completely task irrelevant. For low reward, the opposite pattern was demonstrated in that responses were slower when the target colour remained compared to when it swapped. This response pattern was evident even for a subset of participants informed that after high reward the target colour was likely to swap on the subsequent trial. Despite this, they displayed the same response pattern as those not made aware of this strategy. The inability to ignore a high-reward-associated feature is suggestive of a bias which operates automatically. An N2pc elicited to the same colour on the following trial, regardless of whether it now represented the target or the distractor, confirmed this bias towards the colour associated with a high reward. This was not seen under low reward, suggesting a reduced bias to the colour because it was associated with a less valuable outcome.

Although there is emerging evidence for the role of monetary rewards in visual selective attention, no study to this date has investigated whether such incentive could also influence auditory selective attention. Given that numerous experiments reported in this thesis have failed to replicate well-established findings within the visual domain, this question is particularly pertinent as it seems that the auditory system may in some respects be less open to attentional modulations than is the visual modality. However, with a strong motivational aspect of the task (in this case a monetary reward), it remains possible that the results will be more in line with findings from the visual domain than have been observed in the experiments reported so far in the thesis.

Experiment 11

The present experiment investigated the effect of a monetary reward on auditory selective attention, not only through a behavioural measure but also through EEG recording during task performance. Although research within the visual domain has now reached a stage at which researchers can begin to delineate a top-down influence of reward in terms of increased motivation and a more automatic association between a reward and a specific attribute of the scene (e.g. Anderson et al., 2011b; Hickey et al., 2010; Maunsell, 2004), the current experiment represents the first attempt to examine the influence of reward on auditory attention and thus these more detailed questions were not within its scope.

Although the N2pc component concerns selection of a visual target, a similar negative difference wave relating to attentional focusing on an auditory target has recently been reported for the first time (Gamble & Luck, 2011). Two sounds – a target and a nontarget – were simultaneously presented from individual speakers situated far apart which enabled a clear spatial separation between each sound. The sounds were of four potential identities (a tone, white noise, a frequency sweep, or a click train) and at the start of each block the identity of the target sound was indicated. The task was simply to indicate the presence (vs. the absence) of the target on each trial. The nontarget on each trial was equally likely to be any of the three remaining sounds. Thus, all four sounds constituted both targets and nontargets, and the authors collapsed the different target types into one omnibus analysis. Similarly to the visual N2pc, a significant negativity occurred at the hemisphere contralateral to that of the target location compared with the ipsilateral waveform, around 200 ms after stimulus onset. However, as this negativity was evident on anterior sites (presumably as this is where auditory ERPs are usually identified; Gamble & Luck), this new component was coined the N2ac. It is important however to bear in mind that this finding of an auditory equivalent to the N2pc is based on two experiments alone, using an omnibus exploratory analysis. Despite this, the second experiment strengthened the notion that the N2ac could be described as an auditory component similar to the N2pc, as there was no difference wave evident when a target was presented on its own, which is in line with the N2pc which typically is only elicited (or at least elicited more strongly) when the target is presented amongst competing nontargets (Luck & Hillyard, 1994b).

Rather than using a target detection task as did Gamble and Luck (2011), I used a target discrimination task. One main reason for this difference was to establish whether the N2ac could be elicited for a discrimination tasks as well as for target detection task. This is an important question, because target detection and discrimination presumably involve different levels of attentional focusing. In fact, Luck, Girelli, McDermot and Ford (1997) demonstrated a difference in magnitude of the N2pc depending on whether the task involved detection or discrimination of a target, with the discrimination task leading to a greater N2pc than the detection task. Thus, the present design allowed the possibility of demonstrating a stronger N2ac activation compared with that observed by Gamble and Luck, who indeed demonstrated an N2ac of smaller amplitude (0.5–1 µV) than that which is typically seen with the N2pc (1–2µV). A second reason for the use of a discrimination design concerns the fact that discrimination tasks involve a target being present on each trial, meaning that all trials can be used for subsequent analysis. This was particularly important given that I added the extra factor of monetary reward, which meant an increased number of trials were needed for the analysis. Rather than having four target categories, the target sound in the present experiment could either be a briefly-presented pure tone or a short burst of pink noise. The task was to determine whether the target tone or noise was of high or low pitch whilst ignoring the distractor sound which was always of the different sound category (e.g. noise for tone targets).

While Kiss et al. (2009) manipulated reward through association with a target feature in that participants prioritised fast and accurate responses to a specific target identity, I allocated reward on a trial-by-trial basis. This was to avoid any direct correspondence between the actual target identity (high vs. low pitch) and the reward (high vs. low). A similar reward manipulation on a trial-by-trial basis has previously been established in a visual attention task (Krebs, Boehler, Egner, & Woldorff, 2011) whereby a spatial cue preceded the start of each trial, indicating the location of the target, the difficulty in discriminating the target, and whether successful task performance would result in a reward or not (based on its colour).

fMRI data demonstrated greater activity in areas such as the ventral striatum, posterior cingulate and occipital cortex following a reward cue compared with a no-reward cue. Similarly to Krebs et al., I presented a reward cue prior to the onset of the target and the nontarget sounds. However, rather than manipulating reward vs. no reward, the colour of the cue reflected a potential high or low reward to ensure that participants were motivated to perform well on each trial. This was similar to the kind of reward scheme employed by Kiss et al.

In line with Gamble and Luck (2011), it was predicted that target selection would result in the elicitation of a negative component (N2ac) contralateral to the spatial location of the target sound. This would be an important replication of their findings, and it would also extend them to a task involving target discrimination rather than one of simple target detection.

The second prediction for the current experiment concerned that of the monetary reward. If the reward cue could indeed have an effect on subsequent target selection, it would be expected that the N2ac may be elicited earlier and/or have larger amplitude in the anticipation of a high reward compared to performance on a low reward trial. However, if auditory selective attention proceeds without any such influence, the amplitude and timing of the N2ac wave would not be expected to be any different between the two reward conditions.

Method

Participants

16 participants (one male) were recruited for the experiment. The average age was 22 (ranging from 18 to 26) and one participant was left-handed (female). Participants were paid £15 for their participation, plus up to £10 which was contingent on their task performance.

Apparatus and Stimuli

Sounds were created using the Audacity Software. Similarly to Gamble and Luck (2011), each stimulus was 750ms in duration. The frequency of the target tones were either 400 Hz (low) or 450 Hz (high). The noise targets were created using pink noise, to which a lowpass filter of 1000 Hz was applied for the low pitch noise, and a highpass filter of 1000 Hz for the high pitch noise. All sounds had a rise time and fall time of 10ms, and each sound was written to either the left or the right channel, so that the target and nontarget would appear from different speakers on each trial. Sounds were presented from Logitech Z313 speakers at a sound level of approximately 60 dB SPL.

The cue consisted of a fixation cross subtending 1.1 by 1.1 degrees of visual angle, presented on a 21 inch Sony Multiscan E530 CRT monitor, with a resolution of 1280 × 1024 pixels. On half of the trials the cue was turquoise and on the other half the cue was yellow. The two colours were matched as closely as possible in terms of luminance so that one would not be more physically salient than the other (the luminance of both colours was within 2% of 16.5 cd/m2, measured with a Minolta LS – 100 Luminance meter). The duration of the reward cue was 200 ms, followed by an ISI of 900 ms ± 100 ms prior to the onset of the target and the nontarget sounds.

In each block, either tones or pink noise constituted targets, with the order of target type counterbalanced in an ABBA fashion, such that half of the participants started with tones and the other half started with pink noise. As a previous pilot study found evidence of an association between the target frequency (high vs. low) and the distractor frequency (high vs. low), the identity of the nontarget was blocked with the aim of avoiding or at least reducing such an effect. 12 experimental blocks of 64 trials in each were run, giving a total of 768 trials. Two practice blocks consisting of 12 trials in each preceded the experimental blocks. While these had continuous feedback, the experimental blocks only had feedback at the end of each block.

Procedure

Participants were seated in a dark, electrically shielded chamber, approximately 50 cm from the screen. The speakers were laterally positioned at both far corners of the chamber about 125 cm away from the participants, and each speaker was located 50 cm from the midline.

Participants were informed to remain focused on the fixation cross throughout the experiment, and the task instruction was to report the frequency of the target sound as quickly and as accurately as possible. The target category (tone or noise) was indicated at the start of each block. Half of the participants pressed the 0 key on the numerical keyboard with their right thumb for a low frequency target and the 2 key on the numerical keyboard with their right index finger for a high frequency target. This response pattern applied irrespective of whether the target was a tone or noise. The reverse response pattern was applied to the other half of the participants. The critical reward manipulation, which was delivered via the colour of the fixation cross, was clearly described to participants before starting the task. Thus, they were instructed that the colour of the fixation cross at the start of each trial signalled the degree of a potential reward. For half the participants, fast and accurate responses to the target following a turquoise cue could result in 5 bonus points whereas the same responses to a yellow cue could lead to 1 bonus point. The reverse colour and reward correspondence applied to the other half of the participants. It was emphasised that participants should be extra attentive to the target sound whenever the high reward cue appeared, although to maintain good performance on a low reward trial also. Participants were informed that they could earn up to £10 on top of their payment, which was contingent on their performance on the task. The calculation of bonus points was based on the median RTs of the correct responses in each block. Thus, all RTs below the median RT were awarded with the corresponding points depending on the value of the preceding cue. Participants were encouraged to aim for at least 80 bonus points for each block, and the total points were displayed at the end of every block, in addition to accuracy feedback and general performance feedback based on whether over 80 bonus points were gained or not. After completion of the 12 experimental blocks, total bonus points were calculated and participants were paid up to £10 on top of their base payment of £15 based on how many bonus points they gained (although the minimum pay was £20 regardless of task performance). On average, participants received £23 in compensation.

EEG recording and Analysis

EEG data were recorded using the BioSemi ActiveTwo System. EEGs were recorded the from 64 Ag/AgCl scalp electrode sites positioned according to the 10/20 system on an elastic cap, with the additional recording of horizontal eye movements (HEOG) from two electrodes placed at outer canthi of the eyes, and vertical electrooculogram (VEOG) from electrodes above and below the right eye. Additionally, both earlobes were used as reference sites, and all remaining channels were re-referenced to averaged earlobes post recording. EEG was digitized at a sample rate of 1024 Hz.

Only data with correct behavioural responses were included in the analysis. Data were processed using Eeglab 11_0_4_4b_ (Delorme & Makeig, 2004), an open source toolbox for Matlab, plus the ERPLab toolbox which is closely integrated with EEGLab. Imported EEG data were down-sampled to 512 Hz and high-pass filtered with a .53 Hz cut-off and low-pass filtered with a 40 Hz cut-off. EEG data were segmented into 1000 ms epochs, 250 ms prior to the onset of the sounds and to 750 ms after the onset. The ERP amplitudes were baseline corrected to 200 ms prior to onset of auditory stimuli, as this is the recommended period in order to ensure that as little noise as possible is added to the amplitudes of interest (Luck, 2005). Blinks were removed by running an independent component analysis (ICA) on the epoched data. The ICA identified potential blink and eye movement components which were subsequently removed based on visual inspection of component activations. Thus, components with frontal activity and with a time-window similar to a blink were deleted. Following this, an artifact detection procedure was run using a peak-to-peak amplitude function with a voltage threshold of ±100 µV, in order to detect artifacts other than blinks and eye movements such as muscular artifacts. On average, 9.8% (SD 7.42) of the total trials were removed due to artifacts (compared, for example, with Gamble & Luck (2011) whereby 18.5% and 20.3% of trials were removed in the two experiments respectively). Similarly, to Gamble and Luck, waveforms were collapsed across target type.

For the analysis, electrodes were grouped in to anterior (F1/F2, F3/F4, F5/F6, F7/F8, FC1/FC2, FC3/FC4, FC5/FC6, FT7/FT8), central (C1/C2, C3/C4, C5/C6, CP1/CP2, C23/CP4, CP5/CP6, TP7/TP8) and posterior (P1/P2, P3/P4, P5/P6, P7/P8, PO3/PO4, PO7/PO8, O1/O2) electrode clusters. In line with Gamble & Luck (2011), an analysis was performed separately for each cluster based on the average amplitude over a specific time window. As Gamble and Luck demonstrated an N2ac at anterior electrode sites, the electrodes within this cluster were the main focus for the analysis. However, since to date only one paper has reported on an N2ac, it was important to include the other clusters as the analysis was fairly explorative in nature. While Gamble and Luck saw an increased negativity contralateral to the target location compared to the ipsilateral waveform between 200 and 500 ms measured in 100 ms time windows, visual inspection of the waveform suggested that a potential effect was small and shorter. For this reason, I examined mean amplitude in 50 ms time windows from 200 to 400 ms in this experiment.

In order to investigate the possible occurrence of the N2ac, average contralateral waveforms were compared with average ipsilateral waveforms. That is, average contralateral waveforms included left hemisphere electrodes for targets presented on the right and right hemisphere electrodes for targets presented on the left. For average ipsilateral waveforms, left hemisphere electrodes for targets on the left and right hemisphere electrodes for targets on the right were included. Similarly to Gamble and Luck (2011), I collapsed the waveforms across the four target types to avoid any confounds based on the physical differences between the different targets. In order to ensure that there were no differences in mean amplitude depending on whether the target was presented from the left or the right speaker, this was an added factor to the analysis. Thus, for each electrode cluster, a 4 (time: 200–250ms, 250–300ms, 300–350ms, 350–400ms) × 2 (reward: high, low) × 2 (target position: left, right) × 2 (lateralisation: contralateral, ipsilateral) within-participants ANOVA was carried out to investigate the possible occurrence of the N2ac component and whether its onset and negative voltage amplitude would alter as a function of reward. Given that the focus of the study was to investigate potential auditory lateralisation as a function of a monetary reward, only the significant main effects and interactions in which these two theoretically important factors were involved were analysed further.

Results

Data from two participants were excluded due to technical problems in data recording. Furthermore, one participant was excluded as they expressed before the penultimate block that they had got the reward manipulation wrong, thus they did not fully follow the task instructions.

Behavioural Analysis

For the RT analysis, incorrect responses were excluded, as were responses slower than 2000 ms. RTs were faster for trials preceded by a high reward cue (M = 493 ms) compared with a low reward cue (M = 506 ms; t(12) = 3.23, $p < .005$, d = .177, one-tailed). Error rates were slightly higher for high reward (M = 5%) compared with low reward trials (M = 4%; t(12) = 2.27, $p < .05$, d = .333, one-tailed). To ensure that there were no speed accuracy trade-offs present in the results, inverse efficiency scores were calculated by dividing mean RTs by mean accuracy rates (as discussed in more detail in Chapter 2). Inverse efficiency scores were significantly lower under high reward (M = 517) than under low reward (M = 526; t(12) = 2.06, $p < .05$, d = .116, (one-tailed), suggesting that performance was more efficient for trials preceded by a high reward cue.

Because an association between the frequency of the target and the frequency of the simultaneous distractor was identified during the piloting of the stimuli, it was important to analyse if this effect persisted despite the blocked design implemented to reduce any such effects. RTs were significantly slower when the frequency (high vs. low) of the target was incongruent with that of the distractor (M = 507 ms) compared to when the two were congruent (M = 494 ms), t(12) = 3.06, p < .01, d = .178, one-tailed. Similarly, error rates were higher when the target and distractor were incongruent (M = 6%) compared to when they were congruent (M = 2%), t(12) = 3.3, p < .01, d = 1.05, one-tailed. Thus, although measures were taken to decrease the association between the target and the distractor identity, these effects appeared to persist.

EEG Analysis

Electrophysiology at the anterior electrode cluster. The two top graphs in Figure 11 show the contralateral and ipsilateral waveforms averaged across the anterior electrode cluster as a function of reward (high vs. low). From a visual inspection of the contralateral and ipsilateral waveforms across the whole time window it seems that there is hardly any difference in voltage between the two. This holds true across the two reward conditions.

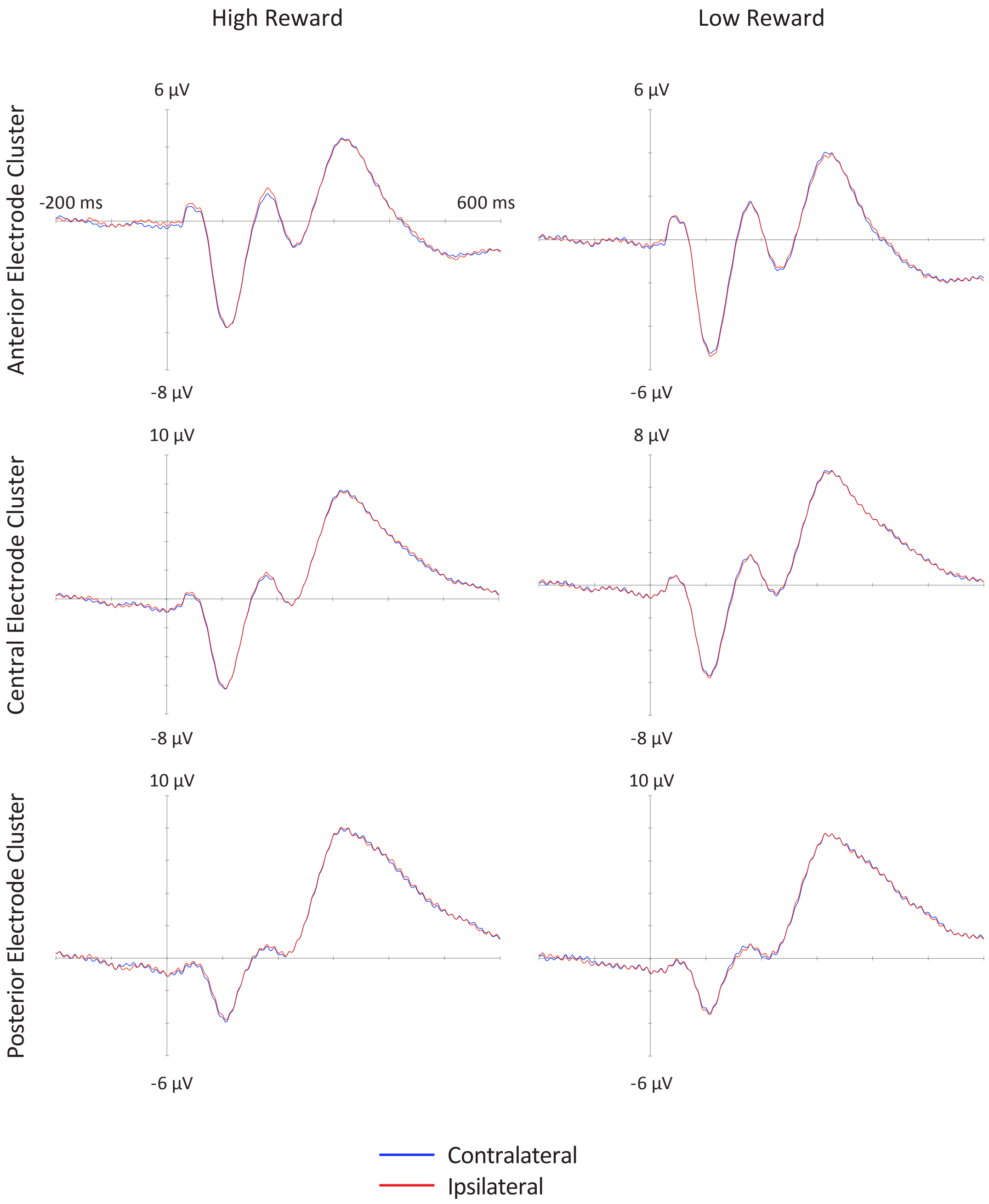

Figure 11. Grand average of the contralateral (blue) and ipsilateral (red) waveforms across the anterior, central and posterior electrode cluster as a function of reward (high, low). (Note that although the statistical analyses only focused on a time window up to 400 ms, the waveforms show voltage up to 600 ms to depict that no major differences occurred outside the time window of interest).

Table 12 summarises the results of the planned ANOVA carried out on the anterior electrode cluster, which overall corresponded with what the waveforms in Figure

11 suggested. There was no significant main effect of lateralisation. However, there was a significant time × lateralisation interaction, which was the most crucial measure in determining the potential occurrence of an N2ac component. Despite the interaction, the post hoc tests all failed to reveal any significant differences between contralateral and ipsilateral targets for the individual time windows, see Table 13. Although there was a trend evident in the 300–350 ms time window, this trend was in the opposite direction with greater negative mean amplitude for the ipsilateral waveform compared with the contralateral waveform. Thus, there was no direct evidence of an N2ac component in the anterior electrode cluster. There was no main effect of reward, and neither did any of the interactions involving reward reach significance, strongly indicating that there was no difference in mean amplitude as a function of whether participants performed a high reward or a low reward trial. There was also a significant Time × Target Position interaction, but since this was not of central theoretical interest of the study it was not followed up further.

Table 12. Summary of statistical analyses for the anterior electrode cluster.

	df	*F*	*MSE*	*p*	η_p^2
Time	2.17, 26.04	21.24	26.04	.001	.639
Reward	1, 12	1.59	7.55	.231	.117
Target Position	1, 12	1.28	.969	.273	.099
Lateralisation	1, 12	.177	.378	.681	.015
Time × Reward	3, 36	1.56	.683	.215	.115
Time × Target Position	3, 36	3.58	.803	.023	.230
Reward × Target Position	1, 12	2.31	1.71	.154	.162
Time × Reward × Target Position	3, 36	.368	.313	.777	.030
Time × Lateralisation	3, 36	2.96	.050	.045	.198
Reward × Lateralisation	1, 12	.693	.231	.421	.055
Time x Reward × Lateralisation	1.93, 23.11	.317	.045	.723	.026
Target Position × Lateralisation	1, 12	4.13	8.17	.065	.256
Time × Target Position × Lateralisation	1.25, 15	.190	3.65	.902	.016

Reward × Target Position × Lateralisation	1, 12	1.21	.361	.293	.092
Time × Reward × Target Position × Lateralisation	3, 36	.760	.045	.524	.060

Table 13. Post hoc tests following the Time × Lateralisation interaction for the anterior electrode cluster comparing contralateral versus ipsilateral waveforms for each time window.

Time	*df*	*t*	*p*	*d*
200–250 ms	12	.618	.548	.024
250–300 ms	12	1.01	.331	.029
300–350 ms	12	1.85	.090	.025
350–400 ms	12	.484	.637	.015

Electrophysiology at the central electrode cluster. The two middle graphs in Figure 11 show the contralateral and ipsilateral waveforms averaged across the central electrode cluster as a function of reward (high vs low). Similarly to the anterior electrode cluster, visual inspection of the contralateral and ipsilateral waveforms across the whole time window suggests for hardly any difference in voltage between the two. Again, there seems to be little difference in voltage between the contralateral and ipsilateral waveforms across reward conditions.

Table 14 summarises the results from the planned ANOVA analysis on the central electrode cluster, and these once again corresponded with what the graphs showed. There was no main effect of lateralisation, and neither was the time × lateralisation interaction significant. However, there was a significant reward × target × lateralisation obtained. Post hoc tests investigated the reward × lateralisation interaction for targets presented to the left and targets presented to the right, respectively. While the reward x lateralisation was not significant for targets presented to the left (F < 1), there was a significant interaction for target presented to the right, F(1,12) = 5.99, MSE = .037, p < .05. However, the post hoc tests following up this interaction failed to demonstrate a significant difference in mean amplitude between contralateral and ipsilateral waveforms both for high reward (t < 1) and for low reward (t(12) = 1.6, MSE = .31, p = .136). Thus overall, once again there was no suggestion of an N2ac component, nor any effect of reward.

Table 14. Summary of statistical analyses for the central electrode cluster.

	df	*F*	*MSE*	*p*	η_p^2
Time	1.65, 19.81	41.55	21.81	.001	.776
Reward	1, 12	2.91	25.69	.114	.195
Target Position	1, 12	.243	2.79	.631	.020
Lateralisation	1, 12	.227	.174	.642	.019
Time × Reward	1.46, 17.47	1.29	1.26	.290	.097
Time × Target Position	1.94, 23.26	1.59	1.53	.226	.117
Reward × Target Position	1, 12	1.22	1.4	.290	.092
Time × Reward × Target Position	1.74, 20.91	.169	.840	.817	.014
Time × Lateralisation	3, 36	1.27	.046	.298	.096
Reward × Lateralisation	1, 12	1.75	.161	.211	.127
Time × Reward × Lateralisation	3, 36	.149	.039	.930	.012
Target Position × Lateralisation	1, 12	1.85	8.3	.198	.134
Time × Target Position × Lateralisation	1.44, 17.22	.395	2.62	.612	.032
Reward × Target Position × Lateralisation	1, 12	4.77	.134	.049	.285
Time × Reward × Target position × Lateralisation	3, 36	.443	.047	.724	.036

Electrophysiology at the posterior electrode cluster. The two bottom graphs in Figure 11 show the contralateral and ipsilateral waveforms averaged across the posterior electrode cluster as a function of reward (high vs low). As with the other electrode clusters, visual inspection of the contralateral and ipsilateral waveforms across the whole time window suggests for very little any difference in voltage between the two. Again, the waveforms do not seem to differ across the two reward conditions.

Table 15 summarises the results from the planned ANOVA on the posterior electrode cluster, which again overall corresponded well with what was displayed in the depiction of the waveforms. Similarly to the anterior and posterior electrode cluster, there was no main effect of lateralisation and reward. Furthermore, neither of the interactions were significant. Overall, there was no evidence for an N2ac component contralateral to the target sound**.**

Table 15. Summary of statistical analyses for the posterior electrode cluster.

	df	*F*	*MSE*	*p*	η_p^2
Time	1.65, 19.78	74.65	23.17	.001	.862
Reward	1, 12	3.53	4.86	.085	.227
Target	1, 12	2.57	2.38	.135	.176
Lateralisation	1, 12	.306	.319	.590	.025
Time × Reward	3, 36	1.6	.460	.208	.117
Time × Target	1.85, 22.21	.584	1.29	.553	.046
Reward × Target	1, 12	.063	1.51	.806	.005
Time × Reward × Target	3, 36	.668	.479	.577	.053
Time × Lateralisation	1.76, 21.13	1.62	.067	.202	.119
Reward × Lateralisation	1, 12	.598	.136	.454	.047
Time × Reward × Lateralisation	3, 36	.391	.072	.760	.032
Target × Lateralisation	1, 12	3.56	7.32	.084	.229
Time × Target × Lateralisation	1.55, 18.56	2.85	1.93	.094	.192
Reward × Target × Lateralisation	1, 12	3.67	.208	.080	.234
Time × Reward × Target × Lateralisation	1.58, 18.95	.172	.256	.793	.014

Scalp Distributions

Because of the spatial nature of the N2pc (and potentially) the N2ac, plotting topographical maps of the voltage distribution using a contralateral minus ipsilateral difference wave is not an appropriate visualisation, because the voltage will fall to zero for the activity around the midline. Similarly to Gamble and Luck (2011), I plotted the scalp distribution of difference waves which were created by subtracting the trials with the target presented from the right speaker from the trials with the target presented from the left speaker. Because of the subtraction, a difference between contralateral and ipsilateral voltages will appear with differences in polarity across the two hemispheres. For a greater negative voltage over the hemisphere contralateral to the target position, a more positive voltage should be seen over the left hemisphere whereas more negative voltage should occur over the right hemisphere. Figure 12 shows the topographical distribution, separated into high and low reward. Interestingly, the high reward scalp distribution shows the predicted pattern depicting more negativity for a contralateral target, particularly over the left hemisphere where the voltage is more positive, around anterior and central positions (which is where the N2ac previously was identified (Gamble & Luck, 2011). The low reward topographical maps, on the other hand, do not show this pattern. However, given the lack of corresponding effects from the statistical analyses, these observations can not bring any further insight into the results from the present experiment.

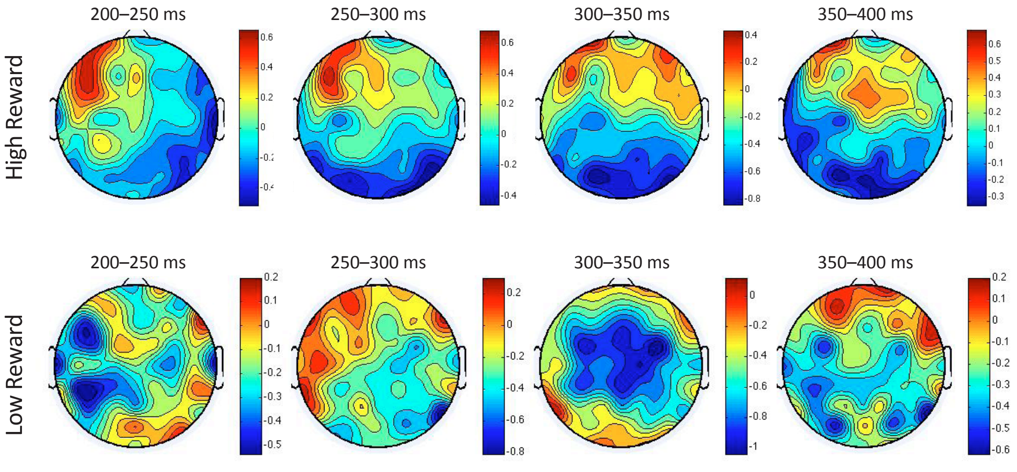

Figure 12. Topographical maps for each 50 ms time window between 200 and 400 ms, as a function of reward (high, low).

Chapter Discussion

The aim of the final experiment of this thesis was to investigate the role of reward on auditory selective attention. In vision, it has previously been established that reward can have a strong influence on attentional selection and task performance (e.g. Kiss et al., 2009; Krebs et al., 2010; Raymond & O'Brien, 2009). To this end, I recorded behavioural responses and EEGs in the presence of two competing auditory stimuli, in a task in which pitch discrimination (high vs. low) was made to the target sound (tone or pink noise). Post recording, the EEGs were time-locked around the time of stimulus onset and averaged to create ERPs. Since the focus of this study was on the effect of anticipation of a potential monetary reward on auditory target processing, ERPs relating to the reward cue preceding the auditory stimuli (which indicated whether that trial was of high or low reward) were not analysed. Instead, the analyses focused on the electrophysiological activations in the presence of the target sound.

The purpose of the ERP analysis was twofold. Firstly, I aimed to replicate the recent suggestion of an auditory analogue of the visual N2pc component which is thought to reflect selection of a target in the presence of competing distractors (e.g. Luck & Hillyard, 1994a; 1994b). The analogous auditory component, coined the N2ac (due to its anterior rather than posterior position) was identified contralateral to the position of a target sound in the presence of a competing nontarget sound, but not when it was presented on its own, which resembles the characteristics of the N2pc (Gamble & Luck, 2011). However, whereas Gamble and Luck employed a target detection task, I used a target pitch discrimination task. Secondly, I investigated whether the N2ac would differ in amplitude and time of onset as a function of reward, in line with Kiss et al., (2009) demonstrating an effect of monetary reward on the onset and amplitude of the N2pc component.

The behavioural results demonstrated faster responses to the target sound in the presence of a high reward cue compared with a low reward cue. The fact that the inverse efficiency score (combining reaction times and error rates) indicated more efficient performance for high (vs. low) reward targets rules out the possibility that a participants traded speed for accuracy and instead suggests that monetary rewards can influence auditory selective attention performance. These findings are in line with increasing evidence in the visual domain demonstrating strong effects of reward on attentional selection using a range of different measures such as distractor interference in a visual search task (e.g. Anderson et al., 2012), negative priming (e.g. Della Libera & Chelazzi, 2006) and the occurrence of an attentional blink in an RSVP task (Raymond & O'Brien, 2009). However, this is the first study to date to demonstrate a similar effect in the auditory domain.

The ERP analysis failed to demonstrate any evidence of an N2ac component. Furthermore, there was also no demonstration of differences in average amplitudes as a function of reward (high vs. low). Since the current study relies on findings from one previous study alone (Gamble & Luck, 2011), it is difficult to identify why no N2ac component was demonstrated in this instance. One difference in the present design compared with that of Gamble and Luck is the nature of the task. While Gamble and Luck used a target detection task, the present experiment used a target discrimination task. Although the N2pc has been identified in a range of different task set-ups (e.g. Luck et al., 1997), it is difficult at this stage to ascertain whether the N2ac would similarly be present in different set-ups. Even though there is evidence for greater N2pc amplitude for a target discrimination task compared with target detection (Luck et al.), it is important to bear in mind that the N2ac cannot necessarily be taken as a direct auditory equivalent of the N2pc, which makes it possible that other parameters might influence the occurrence and magnitude of the N2ac. For example, it might be that the difference in attentional set employed in the two studies may have affected the selection process. While Gamble and Luck's task allowed participants to employ an attentional set based on the fact that they always knew the identity of the target, in the present study the attentional set would have been for either a tone or a noise, but not for a specific tone or noise in particular. Even a relatively subtle difference like this might well affect selection processes and could thus influence whether or not an N2ac is observed. Indeed, previous research has for example demonstrated that attentional set can influence auditory selection, in this case the extent to which a singleton sound captures attention (Dalton & Lavie, 2007). However, further studies are needed to ascertain exactly in what situations the N2ac is present.

It is important to note that, similarly to Gamble and Luck (2011) Experiment 2, the N1 waves in the present experiment were very large. In their case, the N2ac amplitude was considerably smaller under these conditions than it had been in their Experiment 1, perhaps suggesting that a large N1 could reduce the chances of observing the N2ac. Along similar lines, it remains a possibility that the lack of an N2ac in the present study relates to the large N1 observed here. The auditory N1 component is suggested to be elicited by sound onset, and the amplitude is influenced by the physical properties of the sound (Näätänen & Piction, 1987). There could be several reasons as to why the N1 waveforms were of such great amplitude. For example, the intensity of the stimuli used in the present experiment (which was relatively loud) might have affected the N1. Indeed, an increase in stimulus intensity has previously been associated with a greater N1 amplitude compared with stimuli with lower intensity (e.g. Beagley & Knight, 1967). However, whether this in turn would have been a contributing factor as to why the N2ac component was not elicited can only be speculated at this stage.

One significant difference between the present study and the previous study identifying the N2ac component (Gamble & Luck, 2011) was the nature of the distractor sound. Whereas the distractor in the previous study could be one out of three possible identities on each trial and was therefore unpredictable, in the present experiment the distractor was always the same for each block. This was to reduce the potential congruency effects between the pitch of the target (high vs. low) with the pitch of the distractor (high vs. low). However, this predictability might also have reduced the competition between the target and the distractor, in turn meaning that a strong spatial allocation of attention towards the target was not needed. This suggestion is in line with the changing-state effect, which demonstrates that serial recall is typically affected by an irrelevant sequence of sounds only when the sequence consists of different sounds (e.g. Jones, Madden, &

Miles, 1992; Tremblay & Jones, 1998). Thus, repeating the same sound does not impair task performance in this context. However, the changing state effect is typically demonstrated in a crossmodal setting (e.g. Jones et al.), whereby the serial recall aspect relates to visually presented stimuli while the irrelevant stimuli consist of sequences of sounds. Nevertheless, it is possible that a predictable distractor identity – although the distractor location varied from trial to trial – may have significantly reduced its competition with the target, because participants were able to maintain a continuous bias against the predictable distractor.

Conversely, the fact that a distractor effect was seen despite the attempt to reduce such an effect by presenting the same distractor identity in each block, suggests that this interference might have resulted in a reduced spatial focus of the target as the distractor was indeed competing strongly for a response. However, there are not enough unique trials to reliably investigate this possibility.

Another potential reason as to why no evidence of an N2ac component was revealed in this experiment could be due to a lack of power. Although Gamble and Luck (2011) found an effect with similar numbers of participants (i.e. 12 in Experiment 1 and 14 in Experiment 2), it is possible that with an increased number an effect might be revealed. Furthermore, more trials might also have gained the possibility to reveal an N2ac component. Although Woodman (2010) suggested 250 trials per condition for an N2pc, Luck (2013, personal correspondence) argued that about 150 to 200 trials per condition are sufficient. I had 768 trials in total, resulting in 192 trials per condition. Although Gamble and Luck had 312 trials per condition, it was more reasonable to follow Kiss et al. (2009) who had 160 trials per condition as the crucial manipulation in the present study was the reward aspect, and it was of great concern not to make the experiment too long to ensure that participants stayed alert and motivated to respond accordingly with the reward cues. However, as the N2ac magnitude was about half of a normal N2pc (Gamble & Luck), it might be that more trials are needed to discern an effect. Future studies might incorporate the reward aspect with the target (as did Kiss et al.) to reduce the length of each trial, which would allow for more trials for the same total duration of the experiment.

To conclude, the final experiment of this thesis set out to examine the effect of a monetary reward on auditory selective attention, using both a behavioural measure and EEG recording. The behavioural data demonstrated an influence of monetary reward, such that performance was more efficient in the anticipation of a high reward versus a low reward, which is in contrast with the majority of the findings reported within this thesis demonstrating little modulation of auditory attentional selection. However, the ERP results failed to find any evidence of an influence of reward on spatial selection towards the target. Although this failure contrasts the behavioural data, few conclusions can be drawn based on these findings as they relied on very preliminary previous observations (Gamble & Luck, 2011). Thus, Chapter 6 demonstrated that a strong top-down motivation such as monetary rewards could influence the efficiency of attentional selection.

Chapter 7 – General Discussion

The experiments reported within this thesis have investigated several different determinants of auditory selective attention. Since attentional research for about the last 50 years has predominantly focused on the visual domain (Driver, 2001), the main aim of the current thesis was to apply a number of established principles of selective attention in vision to the auditory domain to further delineate to what extent selection processes are similar between the two sensory modalities. Chapters 2, 3 and 4 were concerned with the applicability of load theory to the auditory domain (Lavie, 1995; Lavie et al., 2004), while Chapter 5 considered whether individual differences in reported everyday distractibility could predict levels of distractor processing in a laboratory-based auditory attention task. Finally Chapter 6 manipulated the potential monetary reward associated with a target sound to investigate whether this could affect target selection. Alongside behavioural data collection, EEG recording was carried out to provide a more precise measure of the time window and strength of target selection, and whether this could be influenced by the associated monetary reward.

Overview and Implications

The majority of experiments reported in the thesis have concerned whether load theory holds within the auditory domain. Load theory has proposed two mechanisms that are argued to determine attentional selection. Firstly, the perceptual load in a relevant task is thought to influence whether irrelevant distractors can be successfully ignored. The theory holds that perception is limited, which means that not everything can be processed in parallel. Furthermore, perceptual processing will automatically proceed until this limited capacity is exhausted, leaving no room for flexibility in terms of using up less than the full capacity. Based on these notions, it is argued that with a relevant task which requires a small portion of perceptual resources, there will be spare capacity left which will automatically be allocated to the processing of irrelevant stimuli. Conversely, a high perceptual load task will require the use of all the processing capacity, leaving little or no opportunity for perception of irrelevant distractors. Thus, the theory offered a resolution to the early versus late selection debate by demonstrating that selection can occur either early (with a high load task) or late (with a low load task).

There is now a vast amount of evidence in favour of the notion that perceptual load is a major determinant of successful attentional selection, from both behavioural and neuroimaging studies (e.g. Beck & Lavie, 2005; Forster & Lavie, 2008; Lavie, 1995; Murphy et al., 2012; Rees et al., 1997). However, the majority of the studies have been carried out in the visual domain. As I mentioned in the Introduction, Lavie and Tsal (1994) argued that the same role of perceptual load was also likely to hold within hearing. However, this suggestion has not fully been explored. The Introduction provided an outline of previous studies investigating this very question, and it concluded that the results thus far are mixed. Based on a lack of consensus as to whether the same principles do hold, one of the aims of this thesis was to explore this question further.

In Chapter 2, I set out to test the principles of perceptual load theory by varying the perceptual demands in the relevant task. In Experiments 1 and 2, I varied the number of items in a relevant display, a manipulation of perceptual load widely used in vision (e.g. Lavie, 1995; Murphy et al., 2012). Letter sounds were presented simultaneously, and the task was on each trial to determine the identity of the letter (e.g. X or N, presented in a female voice) whilst ignoring the irrelevant distractor sound (presented in a male voice). Distractor processing was measured through response competition between the target and the distractor, which is a common method of providing an index of irrelevant processing. According to perceptual load theory, distractor interference (i.e. slower responses in the presence of an incongruent distractor compared with a congruent distractor) should be significantly reduced under high (vs. low) perceptual load. While the RT data in Experiment 1 was in line with the predictions of the theory, such that distractor interference was significantly reduced under high perceptual load, the error data showed considerable processing of the distractor (with more errors in the presence of an incongruent distractor compared with a congruent). Thus, overall there was no evidence of reduced distractor processing under high (vs. low) load. Experiment 2 attempted to match the accuracy more closely between the high and low load tasks, to allow a clearer comparison of performance between the two conditions. This was achieved by increasing the perceptual discriminability of each sound. Although the error rates in high and low load conditions were more similar in this instance, the distractor interference did not change as a function of perceptual load. However, note that with the clearer spatial separation between relevant and irrelevant sounds, general distractor interference was reduced by comparison with Experiment 1. Thus, it seemed that with a greater segregation between the individual sounds, participants were generally less susceptible to distractor interference, although this reduction did not change as a function of perceptual load.

Although the first two experiments provided consistent evidence against the perceptual load theory in hearing, there were a few caveats with the design which made it more difficult to draw strong conclusions. Firstly, in visual equivalents of the task set-up, relevant items (target and nontargets) are presented in a specific spatial location although the position of the target varies from trial to trial. In the present experiment, the target was always presented centrally, whereas the nontarget (under high load) was presented to the left or the right. The distractor was also presented either to the left or the right, but never at the same location as the nontarget on a given trial. Therefore, the spatial set-up was not directly equivalent to a visual task set-up. However, the gender distinction between relevant and irrelevant sounds might have acted as a stronger selection cue for the auditory system than the spatial location of sounds (given that space is not as prioritised in hearing as in vision; e.g. Kubovy, 1981), meaning that a clear distinction between relevant and irrelevant sounds is still likely to have been achieved. Secondly, since the load manipulation involved the addition of individual sounds to the task set-up, the discriminability between the sounds was not equivalent between high and low load. The experiments in Chapter 3 were thus designed to overcome these potential confounds.

Temporal separation of auditory stimuli has been suggested to be the closest equivalent to spatial separation in vision (e.g. Kubovy, 1981), and for this reason in Chapter 3 I presented sounds in a rapid sequence, which meant that each sound now had a unique temporal onset. Perceptual load was manipulated by altering the perceptual similarity between target and nontargets, which is commonly done in visual studies (e.g. Beck & Lavie, 2005; Forster & Lavie, 2008). As in Chapter 2, distractor interference was measured through response competition. A significant load manipulation was demonstrated, and there was also a strong interference effect induced by the irrelevant distractor sounds (Experiment 3). However, the distractor interference did not alter due to the level of perceptual load in the relevant task. Because a failure to reveal any load effects could be due to the high perceptual load condition not being perceptually demanding enough (i.e. perhaps imposing only an intermediate level of load), it was important to follow up these results in settings whereby the overall perceptual load effect was significantly increased compared with Experiment 3. Experiments 4 and 5 both demonstrated overall load effects that were greater than the load effect in Experiment 3. Nevertheless, despite this clear increase in perceptual load, there was no evidence of a reduction in distractor processing under high (vs. low) load. Taken together, Chapters 2 and 3 thus provide no evidence that perceptual load would act as a determinant of successful focused attention in hearing as it does in vision.

These findings are in clear contrast to the early suggestion by Lavie and Tsal (1994) that the theory was likely to also hold in hearing. Furthermore, the findings are in contrast with studies demonstrating an auditory perceptual load effect. For example, Alain and Izenberg (2002) used the MMN as a measure of irrelevant distractor processing and found that the MMN in response to a deviant in the unattended channel was significantly reduced under high perceptual load. However, as previously argued, the decrease in MMN in high load conditions might instead have been due to differences in attentional set between the high and low load tasks, rather than a pure modulation by perceptual load on distractor processing. The most promising findings to date for a similar role of perceptual load in hearing as in vision were reported by Francis (2010). A reduction in distractor processing under high (vs. low) load was demonstrated, as measured through response competition. However, traditional evidence for a perceptual load effect is a significant load by congruency interaction, which reveals that the distractor interference is significantly reduced under high load compared with low load. In both experiments, this interaction was not significant ($F < 1$). Instead, the congruency effect (derived from subtracting congruent RTs from incongruent RTs) was significantly modulated, in that it was smaller under high load compared with low load. This failure to find significant results in line with conventional measures somewhat reduces the strength of the findings.

The findings of Chapters 2 and 3 converge with those reported by Gomes et al. (2008). They presented participants with two streams of sounds and measured distractor processing of a deviant sound in the unattended channel through the Nd wave. The difference in amplitude of the Nd wave was in fact in the opposite direction of what was predicted according to perceptual load theory, suggesting that the same principles might not hold in hearing. It is however worth noting that the load manipulation used by Gomes et al. might be open to other influences than perceptual load, which makes it difficult to discern whether the lack of a load effect was a reflection of a genuine load manipulation. Despite this, the converging evidence reported in this thesis implies that perceptual load may not play the same role in hearing as in vision. This has also been suggested by another study performed in our lab which was reported in a recent paper (Murphy et al., 2013) whereby perceptual load in hearing was investigated using a measure of awareness of an irrelevant stimulus rather than response competition paradigm. In line with my findings and with Gomes et al., the reported awareness of a critical stimulus in the unattended channel was no different between high and low load, despite clear evidence of a successful load manipulation. Thus, a consistent lack of a perceptual load modulation has been demonstrated using different manipulations of perceptual load and also different measures of distractor processing. Taken together, these findings all suggest that the selection mechanism might work differently in hearing compared with vision, which I will discuss in more detail in the next section of this chapter.

While there was no evidence of a role of perceptual load in determining auditory selective attention, it remained possible that the other essential mechanism proposed by load theory, which considers the role of available WM capacity in the ability to maintain task focus (e.g. De Fockert et al., 2001; Lavie et al., 2004), might hold in hearing. In contrast to perceptual load, it is argued that an increase in WM load will result in greater distractor interference because of the reduction in cognitive control capacity available to aid in maintaining focus on the relevant task and ignoring irrelevant distractors. Similarly to perceptual load, most of the evidence in favour of WM load has been reported in the visual domain (e.g. De Fockert & Bremner, 2011, Lavie et al.). However, a few recent studies have reported the same effect of WM load on performance on an auditory selective attention task. For example, Dalton et al. (2009) demonstrated more distractor interference from an irrelevant sound when participants were concurrently engaged with a high WM load task compared with a low WM task. In line with this, Dittrich and Stahl (2011) found a stronger auditory Stroop effect under high WM load compared with no load (although only under certain conditions). However, the findings from both of these studies were confined to the possibility that the effect of WM load might have influence processing of the distractor at the stage of response. Chapter 4 therefore sought to investigate whether the role of WM would also hold for distractors that are entirely irrelevant to the task because they do not share any target-defining features with the target, which has previously been demonstrated in vision (e.g. Lavie & De Fockert, 2005).

Experiment 6 used an auditory attentional capture task (Dalton & Lavie, 2004), measuring distractor processing by comparing the RTs in the presence (vs. absence) of an entirely irrelevant singleton distractor sound. A rapid stream of tones was presented, and the task involved making a discrimination concerning the target duration while memorising either a string of five letters presented in random order (high WM load) or in sequential order (low WM load). On half of the trials, an irrelevant singleton of a higher frequency than the other sounds appeared in the stream. Load theory would predict that, due to the high WM load task reducing WM availability for the attention task, the singleton cost associated with the presence (vs. absence) of the distractor should be greater under high compared with low WM load. Indeed, responses were slower in the presence of the singleton distractor compared with its absence. However, the cost was no different under high and low WM load, which is in contrast with the predictions of load theory and also with previous findings demonstrating a role of WM availability in hearing (Dalton et al., 2009; Dittrich & Stahl, 2011).

Similarly to the failure to find a perceptual load effect mentioned above, one could argue that the WM load manipulation was simply not strong enough to reveal and effect in Experiment 6. For this reason, Experiment 7 used exactly the same task but with a WM set of six rather than five digits. Despite this WM manipulation being considerably stronger than that of Experiment 6, the singleton cost yet again remained constant across high and low WM load. Thus, it seems possible that the effect of WM load on auditory selective attention only operates at the level of response, rather than at an earlier stage, and thus modulations by WM load can only be seen when there is response competition between targets and distractors. This is in clear contrast with the findings in the visual domain suggesting that WM load can also operate earlier than at the stage of response (e.g. Ahmed & De Fockert, 2012a; De Fockert & Bremner, 2011; Lavie & De Fockert, 2005). Again, it seems that the auditory system seems to work differently from the visual system in that it appears to be less open to modulations, at least in light of the principles of load theory.

The findings reported in Chapters 2, 3 and 4 are important as they help to further delineate the conditions under which load theory does and does not hold. Recently, load theory has been questioned within the visual domain, with a number of studies demonstrating effects that are difficult to be accounted for by load theory (e.g. Benoni & Tsal, 2012; Eltiti, Wallace, & Fox., 2005; Fitousi, & Wenger, 2011; Tsal & Benoni, 2010; Wilson et al., 2011; Yeshurun & Marciano, 2013). For example, Tsal and Benoni (2010) argued that there is a more plausible explanation for the reduction in distractor processing typically seen under high perceptual load rather than an increase in perceptual demands. Instead, they suggested that adding nontargets to the relevant task leads to more competition between nontargets and distractors for processing, which means that the influence of each individual item gets 'diluted'. This reduction in processing, rather than perceptual load, is argued to be the mechanism behind the reduced distractor interference that is typically observed in high perceptual load conditions. In support of this claim, they presented experiments whereby the same set-up as the early study by Lavie (1995) was used. However, alongside the normal low and high perceptual load tasks, there was a dilution condition which consisted of a target presented amongst nontargets. While this would typically be considered a high load task, the authors argued that it was of high dilution because of the nontargets competing for processing, but of low perceptual load because of the task requirements. For example, in one experiment (Experiment 2) the neutral letters were presented in the periphery (either to the left or the right) rather than at the same location as the target, while the distractor was also presented in the periphery but on the opposite side from the nontargets. They demonstrated that despite the task being of low perceptual load, processing of the distractor was reduced, which is difficult for perceptual load theory to reconcile.

However, in light of this criticism against perceptual load theory, it is very important to note that the failure to demonstrate a role of perceptual load or WM load in hearing by no means provides a criticism of the theory in the visual domain. Although the alternative dilution theory (e.g. Benoni & Tsal, 2012; 2013) has attempted to provide a better explanation as to why distractor processing is reduced under high load, it fails to account for the wide range of findings that have supported perceptual load theory. For example, it struggles to provide an alternative explanation for task set-ups which manipulate perceptual load by varying the perceptual similarity between target and nontargets while keeping the number of items in a display constant. Thus, load theory remains a prominent theory of selective attention within vision, despite the fact that it does to appear to hold reliably within hearing.

Whereas Chapters 2–4 reported findings based on results at a group level, Chapter 5 presented experiments considering individual differences in auditory distractor processing. More specifically, Chapter 5 aimed to link performance on a laboratory task of auditory selective attention with scores from a self-report measure of everyday distractibility known as the CFQ (Broadbent et al., 1982), which has previously been shown to relate to performance on visual selective attention tasks (e.g. Forster & Lavie, 2007; Tipper & Baylis, 1987). While score on the CFQ did not predict auditory distractor processing on flanker tasks measuring response competition effects (Experiments 8 and 9), Experiment 10 demonstrated a relationship between CFQ score and performance cost in the presence of an irrelevant singleton sound, such that a higher score (indicating greater occurrence of everyday cognitive slips) resulted in more errors in the presence (vs. absence) of an irrelevant singleton distractor. These findings suggest that the auditory attentional capture task used (which was based on one developed by Dalton & Lavie, 2004) measures performance that can be linked with everyday behaviour. This is an important demonstration as cognitive psychology experiments often are considered to be reasonably far removed from behaviour outside the laboratory. However, this is not to say that the two flanker tasks used (in Experiments 8 and 9) do not reflect any real life behaviour, only that they do not correlate with what the CFQ measures. Experiment 10 was the first study to date to demonstrate that CFQ score can predict performance on an auditory selective attention task, which is in line with previous reported relationships within vision (e.g. Forster & Lavie; Tipper & Baylis). Given that very few items on the questionnaire reflect cognitive slips related to auditory distraction, it seems likely that the CFQ corresponds with more general executive functions. Furthermore, there are many demonstrations of individual differences in both visual (e.g. Ahmed & De Fockert, 2012b) and auditory distractor interference (Conway et al., 2001) based on WM capacity, so it might be that the CFQ more specifically reflects differences on this aspect. Future studies should aim to explore this possibility further.

The modulation of distractor interference with reported individual differences in the extent to which the presence of an irrelevant singleton sound resulted in an erroneous response towards the target is important in light of the findings in Chapter 2–4. Even though there seems to be little evidence of a modulation on auditory distractor processing as a function of the principles of load theory, Chapter 5 did indeed demonstrate that there is scope for differences at an individual level, although this relationship seems to depend on the nature of the task at hand.

The final determinant of auditory distractor processing that was investigated in this thesis was monetary reward. A monetary gain can be considered a particularly strong top-down motivation to perform well on a relevant task, as has been widely demonstrated in vision (e.g. Anderson et al., 2011a; Hickey et al., 2010; Raymond & O'Brien, 2009). Chapter 6 demonstrated the first findings of an influence of a potential monetary reward on a trial-by-trial basis on task performance on an auditory target discrimination task (Experiment 11). Target selection was faster when the preceding visual cue indicated a high (vs. low) reward for a fast and accurate response. This finding remained when a potential speed accuracy trade-off was taken into account. Thus, the findings were in line with previous visual studies reporting an influence of reward whereby the effect is likely to reflect a motivational increase to selectively attend to the relevant stimuli when the potential monetary reward is high versus low (e.g. Della Libera & Chelazzi, 2006; 2009). However, these findings were only present in the behavioural data. The ERP results showed no evidence of the N2ac in response to target selection. Furthermore, the ERPs were no different as a function of reward. This is in contrast with previous studies demonstrating greater amplitude in response to a high (vs. a low) reward target (Kiss et al., 2009; Hickey et al.). However, the modulation of reward on the ERPs relied on identifying the N2ac, which makes it difficult to draw any conclusions based on this study alone as the N2ac was not evident. The potential reasons as to why a failure to observe an N2ac occurred in the present experiment are manifold. First of all, the N2ac has only been reported once before (Gamble & Luck, 2011), with small effects. Experiment 11 did not provide a straight replication of the previous design, which makes it possible that the effect is only confined to specific task set-ups. Given the small amplitude, this possibility in fact seems highly likely. Note that although there is evidence for spatial auditory selectivity (Gamble & Luck), Luck argued that hearing might be less lateralised than vision (personal correspondence, 2013), perhaps making it more difficult in general to observe an N2ac than an N2pc. For this reason, it is of great importance to attempt to replicate the observation of the N2ac before firm conclusions on this matter can be made.

Another important contribution of the work described within this thesis has been the establishment of two new flanker tasks. Previously, only one study has attempted to replicate the visual flanker task in hearing by demonstrating that congruency effects from an irrelevant distractor also exist within the auditory domain (Chan et al., 2005). A target word was presented centrally (i.e. 'bat' or 'bed') while two distractors were flanked to the left and the right, respectively. The distractors were either congruent or incongruent with the target word, and performance was reported to be significantly worse in the presence of an incongruent distractor compared with a congruent distractor despite the target always being presented in the same spatial location. The two flanker tasks developed as part of the work of this thesis are important additions to the task designed by Chan et al. because they consist of a less complex set-up. While Chan et al. used multiple speakers (e.g. at least three) to present the three sounds, Experiments 1, 2 and 9 demonstrated that spatial separation between stimuli that is required for a successful auditory flanker task of this type can be achieved with the use of two speakers. This method has the advantage of allowing presentation of the task stimuli over headphones, increasing the perceived spatial separation between left, right and central stimuli to maximal levels. Furthermore, while the task used by Chan et al. and the flanker task used in Experiments 1, 2 and 9 used a simultaneous presentation (which involves the additional complexity of masking), the flanker tasks used in Experiments 3, 4, 5 and 8 adopted a sequential presentation method which has the advantage of allowing each sound to be presented with a unique onset. Although a sequential presentation of sounds also can involve a degree of masking (e.g. Oxenham & Wojtczak, 2009), these effects are likely to be much less pronounced than those of simultaneous masking. In addition, overall this method might be argued to reflect a more natural way in which sounds unfold over time rather than appearing simultaneously but separated in space (e.g. Kubovy, 1981).

Differences Between Visual and Auditory Selection

The consistent failure to demonstrate an effect of perceptual load on auditory distractor processing raises intriguing questions concerning the ways in which perceptual demands might be handled differently in hearing than in vision. Perceptual load theory argues that selection occurs whenever processing capacity has been exhausted. This in effect means that irrelevant distractors can only be prevented from causing interference if the relevant task is perceptually demanding enough to use up all capacity. In response to their failure to find an effect of perceptual load, Gomes et al. (2008) argued that there might be more flexibility in the auditory system, compared with the automatic proceeding of exhausting processing capacity in vision. Thus, they suggested a less passive system whereby some capacity might voluntarily be left, allowing for detection of unexpected changes. However, there was no attempt in explaining the mechanisms behind this proposed voluntary flexibility. Instead, there might be a more simple way to explain the failure to find an effect of perceptual load despite clear evidence that the perceptual demands are significantly larger under high versus low perceptual load (Experiments 1–5).

As suggested in the Chapter Discussion of Chapter 3, it seems possible that this difference in how perceptual demands are handled in hearing compared with vision stems from substantial contrasts between the selection mechanisms operating in the two modalites. While perceptual capacity is allocated to a spatial area which is determined by where the eyes focus, and which clearly prioritises stimuli that fall on the fovea (since this area has been shown to be over-represented throughout visual processing; e.g. Azzopardi & Cowey, 1993), hearing does not seem to possess an equivalent mechanism allowing perceptual capacity to be focused so strongly on a specific portion of the auditory input. Although it is possible for the auditory system to selectively attend to a relevant stream, it seems unlikely that all processing capacity is dedicated to that stream alone. For this reason, it might be the case that auditory distractors can almost always receive some level of processing, in addition to processing of the relevant stream. According to the findings in Chapters 2 and 3, along with other findings from our lab (Murphy et al., 2013) and Gomes et al. (2008), it seems that this is possible even when the relevant stream imposes significant perceptual demands. In fact, processing of the irrelevant distractors was no different under high and low load in these experiments, without an indication of even a slight reduction under higher perceptual demands (e.g. Chapter 3). In line with this observation, it is important to note that the strongest evidence to date in favour of perceptual load theory in hearing (Francis, 2010) also demonstrated considerable distractor processing under high perceptual load. More specifically, the high load congruency effects (incongruent RTs–congruent RTs) were 91 ms and 77 ms in the two experiments Francis reported. Even though these effects were significantly reduced compared with low load, the irrelevant distractor was clearly processed reasonably extensively under high load. Although some congruency effects might also be seen under high load also in visual studies, they are typically not of this magnitude. However, one could still simply argue that the high load in Francis's experiments was not perceptually demanding enough, but rather of an intermediate load, since a reduction in interference was clearly evident as perceptual demands increased. It is thus still possible that with a task requiring an extremely high level of processing capacity there might be no or very little distractor processing evident. However, the convergent evidence (e.g. Experiment 1–5; Gomes et al.; Murphy et al.) suggests that irrelevant auditory stimuli are likely to be processed regardless of the level of load in the task one is currently engaged with.

Support for this suggestion can be found in the MMN literature. Generally, it seems that an MMN is elicited in the presence of a deviant sound even in an unattended channel (Sussman, 2007; Näätänen et al., 2007). Thus, it seems like the auditory system is most often able to detect changes in the environment, despite attention being focused elsewhere. This was for example demonstrated in a study whereby participants focused their attention to the sounds presented as part of a video (Winkler, Teder-Sälejärvi, Horváth, Näätänen, & Sussman, 2003). Irrelevant sounds were played in the background, such as traffic noise and footsteps. On some trials, there was a deviant footstep presented. The EEG results demonstrated an MMN elicited towards the deviant footstep, despite this being entirely irrelevant to the task. This finding demonstrates that the auditory system seems to be able to pick up changes in the environment even when the processing capacity is focused elsewhere. However, as mentioned in the introduction, findings like these have rarely manipulated perceptual demands of the relevant task, so it still remains possible that a reduction in processing of the unattended stream would be evident with a more demanding task. Note that even with studies demonstrating a reduction in processing of irrelevant sounds, this is not always a consistent finding (Chait et al., 2012). In their study, cortical responses to a change in an irrelevant stream of sounds were only reduced under high (vs. low) load when the change involved a random pattern turning in to a frequent pattern. Although I made the claim in the Introduction that this study specifically did not manipulate perceptual load per se, the findings still converge with the majority of findings reported in this thesis (i.e. Experiment 1–9) which have generally demonstrated that it seems likely that the auditory system is much less open than the visual system to any modulation in terms of the extent to which distractor processing occurs. It seems that only in some highly restricted circumstances is it possible to change the extent of auditory distractor processing that is observed. This is also true for the contradictive findings in Chapter 4 whereby processing of the irrelevant singleton distractor sound was no different under high and low WM load, while previous studies using a response competition paradigm demonstrated modulation of distractor processing as a function of WM load (Dalton et al., 2009, Dittrich & Stahl, 2011).

As discussed in the Introduction, perceptual load theory is formed around a number of operational definitions which are difficult to precisely quantify. For example, the number of items in a relevant search display determines the level of perceptual load in a relevant task. While in vision, a high perceptual load display seems to consist of four or more items (Lavie & Cox, 1997); a high perceptual load display in hearing might be induced with two sound sources (as suggested in Chapter 2). However, although perceptual load was suggested to be increased due to main effects of load throughout all five experiments (in Chapter 2 and 3), distractor processing was no different between high and low perceptual load, which is not in line with the principles of the theory. Since the theory simply hinges on a successful difference in RTs and/or error rates between high and low load, one could always argue that the load manipulation was not strong enough to exhaust processing capacity, despite being significant greater under high (vs. low) load. This assumption creates a circular argument which is difficult to untangle. In light of the present findings, the operational definitions of perceptual load appear to be of little use. It might also be that other operational definitions are needed for a different sensory modality, in that for example the number of items in a relevant display applies much better to vision than to hearing. Given the inherent differences in which auditory and visual information is processed, it remains possible that the way in which processing capacity is exhausted relies on different parameters. However, as argued throughout the thesis, it seems possible that the auditory system is more likely at all times to retain some spare capacity, allowing for detections of important changes in the environment.

However, similarly to vision, auditory selection does seem to be influenced by a monetary reward associated with a target, which demonstrates that a strong top-down control can exert influence on attentional control. It is however possible that the efficient target selection under high reward was simply down to a strategic slowing in responses under low reward trials, rather than a genuine effect of top-down control in response to the high reward cue. While the EEG data potentially offered the opportunity to more closely investigate the influence of reward, unfortunately the results remain inconclusive. Future studies should first of all attempt to replicate the N2ac, and if a robust effect is evident examine whether the signature of attentional selection alters as a function of reward. Alternatively, one might be able to measure the MMN in response to an unattended deviant and investigate whether it changes as a function of reward in response to the relevant stimuli (although as previously argued it seems possible that the MMN response might occur independently of attention (e.g. Sussman, 2007)). Furthermore, Experiment 11 did not provide a direct measure of distractor processing. It would therefore be interesting to examine whether an influence of reward could affect performance cost in an attentional capture paradigm, either by associating one target type with a high reward and the other with a low reward or, similarly to Experiment 11, by cueing participants about high (vs. low) reward on a trial by trial basis.

It would also be interesting to combine a reward manipulation with a manipulation of visual perceptual load to investigate whether reward associations could in fact *override* perceptual load modulations (such that a high reward under low perceptual load could result in reduced distractor interference, similarly to exhausting processing capacity through high perceptual load). If the same pattern as predicted by load theory would emerge even under the influence of a high monetary reward, this would provide a strong case for perceptual load as a determinant of successful selection as the effect would hold even when a strong top-down control is exerted to ignore irrelevant distractors. On the other hand, if the influence of reward were to override the perceptual load modulation, this would provide strong evidence that it is not solely the perceptual demands of a relevant task determining whether distractors can successfully be ignored, but also other mechanisms such as the strong top-down motivation provided by a monetary reward.

The failure to find a modulation of perceptual load in hearing suggests that the theory might not hold across all sensory modalities. It is therefore interesting to ask whether perceptual load would determine successful selective attention within other senses such as touch. It is known that tactile information must be selectively processed, such that large amounts of input are continuously ignored (e.g. the feel of our clothes against the skin; e.g. Holmes & Spence, 2006). There have also been previous suggestions of inattention towards a tactile stimulus when attention is otherwise engaged (Mack & Rock, 1998). However, the question remains whether the ability to ignore irrelevant tactile information is determined by the perceptual load in the relevant task. To this date, there have been few direct investigations into this question. However, Adler, Giabbiconi and Müller (2009) reported two experiments, one using a tactile target detection task (low perceptual load) and one using a tactile target discrimination task (high perceptual load) which was presented to one side of the body. Greater interference from tactile distractors presented to the unattended side of the body was demonstrated in the low perceptual load study than in the high perceptual load study. This provides some preliminary suggestion that perceptual load might indeed hold in touch.

Conclusions

Overall, the work presented in this thesis has aimed to further the understanding of auditory selective attention, by taking established determinants of visual selective attention and investigating whether the same principles would apply to hearing. Based on the mixed pattern of existing findings concerning whether perceptual load theory would also hold in hearing (Lavie, 1995), I set out to investigate further whether the perceptual demands of a relevant task can determine auditory distractor processing. I consistently failed to find any evidence in favour of perceptual load theory, which led me to conclude that auditory distractor processing might be less open to modulation than visual distractor processing, possibly because of the differences between auditory and visual selection mechanisms. In particular, I have argued that the auditory system might retain some spare capacity to process irrelevant sounds, regardless of the perceptual demands in the attended stream. I also failed to find any evidence of the role of WM availability in the extent to which auditory distractor processing occurs, in a context in which these distractors werre entirely irrelevant to the task. Overall, these findings suggest that auditory attentional selection is less open to modulations than is vision.

However, I have demonstrated some evidence that there might be a relationship between individual differences in reported everyday distractibility and the extent to which auditory distractor processing occurs, although this was a somewhat inconsistent finding. It thus seems that the relationship depends largely on the specifics of the task paradigms used to provide the laboratory measure of distractor interference. I have also shown some evidence that attentional selection of an auditory target in the presence of a nontarget can be enhanced when the task is associated with a high (vs. low) monetary reward. This demonstrates that similarly to vision, the auditory system seems able to be influenced by particularly strong top-down influences such as reward.

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Appendix

The Cognitive Failures Questionnaire (Broadbent, Cooper, FitzGerald & Parkes, 1982)

The following questions are about minor mistakes which everyone makes from time to time, but some of which happen more often than others. We want to know how often these things have happened to you in the past 6 months. Please circle the appropriate number.

		Very often	Quite often	Occasionally	Very rarely	Never
1.	Do you read something and find you haven't been thinking about it and must read it again?	4	3	2	1	0
2.	Do you find you forget why you went from one part of the house to the other?	4	3	2	1	0
3.	Do you fail to notice signposts on the road?	4	3	2	1	0
4.	Do you find you confuse right and left when giving directions?	4	3	2	1	0
5.	Do you bump into people?	4	3	2	1	0
6.	Do you find you forget whether you've turned off a light or a fire or locked the door?	4	3	2	1	0
7.	Do you fail to listen to	4	3	2	1	0

	people’s names when you are meeting them?					
8.	Do you say something and realize afterwards that it might be taken as insulting?	4	3	2	1	0
9.	Do you fail to hear people speaking to you when you are doing something else?	4	3	2	1	0
10	Do you lose your temper and regret it?	4	3	2	1	0
11	Do you leave important letters unanswered for days?	4	3	2	1	0
12	Do you find you forget which way to turn on a road you know well but rarely use?	4	3	2	1	0
13	Do you fail to see what you want in a supermarket (although it’s there)?	4	3	2	1	0
14	Do you find yourself suddenly wondering whether you’ve used a word correctly?	4	3	2	1	0
15	Do you have trouble making up your mind?	4	3	2	1	0
16	Do you find you forget appointments?	4	3	2	1	0
17	Do you forget where you	4	3	2	1	0

	put something like a newspaper or a book?					
18	Do you find you accidentally throw away the thing you want and keep what you meant to throw away – as in the example of throwing away the matchbox and putting the used match in your pocket?	4	3	2	1	0
19	Do you daydream when you ought to be listening to something?	4	3	2	1	0
20	Do you find you forget people's names?	4	3	2	1	0
21	Do you start doing one thing at home and get distracted into doing something else (unintentionally)?	4	3	2	1	0
22	Do you find you can't quite remember something although it's "on the tip of your tongue"?	4	3	2	1	0
23	Do you find you forget what you came to the shops to buy?	4	3	2	1	0
24	Do you drop things?	4	3	2	1	0

25	Do you find you can’t think of anything to say?	4	3	2	1	0

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