THE ROLE OF PERCEPTUAL LOAD AND SENSORY DEGRADATION ON CROSS–MODAL SELECTIVE ATTENTION

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The role of perceptual load and sensory degradation on cross-modal selective attention.

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Abstract

To understand our sensory environment, our perceptual system must employ selective attention; the ability to attend to target information while ignoring distracting information. In the uni–modal domain the main determinant of selective attention success is capacity limitation, where only when processing capacity is taxed by the target (high load; HL) is distraction eliminated (perceptual load theory; PLT). Conversely, data limits while also increasing task demands, do not benefit selective attention as these limits are often driven by sensory degradation (SD) such that placing additional resources towards the target is not beneficial. Investigations of PLT to the cross–modal domain have produced mixed results, and no study has yet directly contrasted the impact of capacity and data limits in the cross–modal domain. The present dissertation focused on examining the impact of Perceptual Load (PL) and SD on cross–modal selective attention, in addition to examining how these factors would interact with the attended modality and individual differences (ID) in attentional control. Experiment 1 used a go–no–go manipulation of PL to show that distractor effects were not reduced at HL compared to low load (LL) condition and instead displayed trends for increased distraction under HL regardless of the attended modality. Experiment 2 used the addition of noise to create SD, and found that distractor processing increased under SD, again regardless of the attended modality. Experiment 1 and 2 used a uni–modal measure of attentional control, and overall both studies did not find a consistent pattern of correlation with cross–modal selective attention, suggesting important differences between the two. Experiment 3 used a single manipulation to create HL and SD conditions in a single experiment, and also found that both HL and SD showed trends of increased distraction relative to LL conditions. Overall the current dissertation suggests that capacity limitations arise at the modality level, and so do not impact cross–modal selective attention. As such, the findings of the current dissertation suggest there is no difference between capacity and data limited conditions in the cross–modal domain. Results are interpreted within a cross–modal selective attention framework.

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Chapter 1: General introduction

General introduction

Our daily sensory environment is very complex, and at any given time may provide information arising from multiple sensory modalities. Furthermore, our senses are constantly bombarded with multiple stimuli, both from within a single modality as well as from different modalities, and attention is thought to be the mechanism that selects goal–relevant (target) stimuli for further processing.

While selective attention is an important mechanism in preventing sensory overload, it is not always successful (e.g., Eriksen & Eriksen, 1974; Gatti & Egeth, 1978). A classic example of the failure of selective attention is the Stroop task (Stroop, 1935). First used in the visual domain, a typical Stroop task involves written colour words, for example the word “blue”, printed in either a matching colour (congruent trials, in this case blue), or in a mismatching colour (incongruent trials, in this case red). Participants are asked to either read the word and ignore the colour or to report the colour and ignore the word. When asked to report the colour and ignore the written word, large interference effects are observed on incongruent trials in terms of reaction times and error rates, suggesting that participants are not successful at ignoring the written word.

In addition to the Stoop task (Stroop, 1935) and other paradigms in the visual domain (e.g., inattentional blindness; Simons & Chabris, 1999) and the auditory domain (e.g., dichotic listening; Cherry, 1953), the ability of selective attention has also received research interest in the cross–modal domain. As noted above, our senses are often simultaneously bombarded with information from different sensory modalities, and thus it is equally import to be able to selectively attend to information provided by a specific (goal–relevant) modality and ignore information in irrelevant modalities. Similar to the uni–modal domain, research has demonstrated failures of selective attention across modalities (e.g., Chen & Spence, 2010; Chen & Spence, 2011; Driver & Baylis, 1993; Giard & Peronnet, 1999; Laurenti, Kraft, Maldjian, Burdette, & Wallace 2004; Molholm, Martinez, Shpaner, & Foxe, 2007; Saldana & Rosenblum, 1993; Shore & Simic, 2005). For example, a cross–modal version of the Stroop task conducted by Laurenti et al. (2004), demonstrated typical Stoop interference effects consistent with uni–modal findings. That is when a spoken colour word and a visually presented colour patch represented different colours participants were significantly slower at naming the colour patch, relative to trials in which the colour patch was presented alone, or was presented with a matching spoken colour word.

In the cross–modal Stroop paradigm used by Laurenti et al., (2004) the audio and visual signals arose from the same space, at the same time, and the information from the two modalities had a semantic relationship, in that there was a relationship between the information in the two modalities. Importantly, all of these three factors, spatial correspondence (Driver & Spence, 2004), temporal correspondence (see Spence, 2007, for a review) and semantic relations (see Doehrmann & Naumer, 2008, for a review), are thought to promote multisensory integration. Driver and Spence (2004) reviewed research on cross–modal spatial attention that demonstrated the relative ease of attending to multiple modalities (divided attention) when they arise at the same, compared to a different, spatial location. Importantly the authors note that the corollary of this is also true; it is more difficult to selectively attend to a single modality when other sensory information is presented at the same location as the attended information. For example in a study by Spence, Ranson and Driver (2000), the authors presented auditory distractors at various distances from a visual target. They found that the influence of the distractors decreased as the distance from the visual target increased, thus demonstrating the impact of spatial correspondence on cross–modal selective attention.

Similar effects of temporal and semantic correspondence on cross–modal selective attention have also been demonstrated in the literature (e.g., Chen and Spence, 2010; Applebaum, Meyerhoff and Woldorff, 2009). In a study by Chen and Spence (2010) participants had to name the naturalistic object represented by an image that was presented briefly before being masked. The image was presented with an auditory sound that represented the same object (congruent trials), represented a different object (incongruent trials) or was neutral (white noise). Furthermore, the sound could be presented simultaneously with the image or after the image (300 and 533ms). The impact of semantics was demonstrated by facilitation and interference on congruent and incongruent trials relative to neutral trials. The impact of temporal correspondence was demonstrated by the fact that while both facilitation and interference effects were observed during simultaneous presentation, only facilitation was seen at intermediate stimulus onset asynchrony (SOA; 300 ms), and neither facilitation nor interference of auditory information was seen at the longest SOA (533 ms). Thus, selective attention was successful (no facilitation or interference of auditory information on picture naming) only when auditory and visual information were not presented in close temporal proximity.

The results above demonstrate that the factors which promote multisensory integration also have the converse effect of making selective attention to a modality more difficult. While the effects of the above factors, especially spatial and temporal correspondence on cross–modal processing, have been extensively examined (e.g., Fendrich & Corballis, 2001; Meredith & Stein, 1987; Morein–Zamier, Soto–Faraco & Kingstone, 2003; Navarra, Soto–Faraco & Spence, 2007; Readeau & Bertelson, 1997; Sugita & Suzuki, 2003; for a review see Spence, 2007) the current dissertation focused on additional factors that may also contribute to the success/failure of cross–modal selective attention. Specifically, I was interested in the effects of cross–modal perceptual load (PL; Experiment 1) and sensory degradation (SD; Experiment 2) on cross–modal selective attention/distractor processing[1]. While increasing PL and increasing the extent of SD both increase task difficulty, they appear to have opposite effects on distractor processing (e.g., Lavie 1995; Yuval–Greenberg & Deouell, 2009), at least in the within–modality case. Thus, I was also interested in directly comparing the effects of cross–modal PL and SD on cross–modal distractor processing (Experiment 3). In addition, in all three experiments I was interested in examining the impact of attended modality, and as such all experiments contained attend–audition and attend–vision conditions. Finally, since selective attention is also thought to depend on variable degrees of personal attentional control, I was interested in assessing the impact of individual differences (ID) in attentional control on cross–modal distractor processing, and any potential interactions with cross–modal PL and SD. The following review of literature will present an overview of early versus late selection models of selective attention, followed by a review of perceptual load theory (PLT). Then the impact of SD and PL on selective attention will be considered. The findings on the impact of individual differences in attentional control on selective attention will be presented, followed by a brief overview of the goals of the experiments in the current dissertation.

Theories of selective attention

In our everyday experiences of our sensory environment only some sensory information is relevant to current goals. The mechanism by which humans select and process relevant information while ignoring irrelevant information has been highly debated in psychological

[1] Note that terms selective attention and distractor processing will be used interchangeably throughout the dissertation.

literature for over a century (see Driver, 2001 for a review). While researchers agree that there exists a selection mechanism, the debate has focused primarily on where selection takes place along the processing stream from perception to action. Until relatively recently, there have been two main categories of models, those which propose that selection takes place early in the processing stream (e.g., Broadbent, 1958; Treisman, 1960: early selection models) and those which propose that selection takes place later in the processing stream (e.g., Deutsch and Deutsch 1963; late selection models). Lavie (1995) has suggested a hybrid model in which selection can occur either at early or late processing stages, with the specific locus of selection determined by the PL of the task. In the following selection a brief review of literature on early and late selection models, followed by an examination of PLT is presented.

Early vs. late selection models

The first model of selective attention was put forth by Broadbent (1958). He suggested a two stage early selection model termed 'Filter Theory'. In the first stage, the physical properties (e.g., pitch, colour, orientation) of all stimuli would be processed (in parallel) and stored in immediate memory in a pre–categorical manner. Unlike the first stage, he suggested that the second stage, during which semantic information was extracted (post–categorical), was subject to extreme capacity limits. As such, he suggested a filter between stage one and stage two. Broadbent claimed that the filter worked via the selection of a particular channel of information for further processing. Specifically, he suggested that people attend to particular physically definable streams of information, and selection was based on the attend stream (channel). He further suggested that channel selection was based on a combination of top–down (e.g., goals) and bottom–up (e.g., saliency) factors. Given that the filter in this model directs selection based on basic physical properties, this model is considered an early selection model in which all stimuli do not go forward to semantic analysis.

Broadbent's (1958) model was able to account for early dichotic listening tasks such as the cocktail party effect. This effect refers to people's ability to focus on a specific speaker/conversation in a room which is filled with multiple speakers/conversations. Cherry (1953) used a dichotic listening paradigm to study this effect empirically by presenting participants with one stream of information in one ear, and another in the other ear, and asked participants to repeat (shadow) information from one stream/ear only. These studies found that participants were successful in shadowing information from the attended stream. In the unattended stream, they were able to report basic physical properties (such as pitch changes, presence of linguistic information) however, they were unable to report specific semantic information from the unattended stream (e.g., recall a word that was repeated in the channel).

However, evidence began to accumulate calling into question the position of Broadbent's filter. Building on Cherry's paradigm, Moray (1959; see also Wood and Cowan, 1995) placed the participants' names in the unattended stream. Following the task, participants were asked if they had heard anything in the unattended stream, and found that individuals often reported hearing their names. This observation directly contradicts Broadbent's model, as it shows semantic level processing of unattended stimuli. Further criticism of Broadbent's theory was the use of explicit measures to assess the level of processing that the unattended stimuli received. For example, in dichotic listening paradigms it could be the case that all stimuli were processed at the semantic level; however, only some of them entered into memory. Using an implicit measure, Corteen and Dunn (1974) were able to show that unattended stimuli could in fact receive processing at the semantic level without entering into memory. In their experiment, the authors fear–conditioned participants to certain words by presenting them alongside an electric shock. Then in a typical dichotic listening paradigm, the fear–conditioned words were placed in the unattended stream, and the authors found they produced increased galvanic skin responses (GSR). Importantly, when participants were asked to report if they had heard the fear conditioned words, they typically did not report hearing them, highlighting potential limitations of explicit measures of distractor processing.

Subsequent modifications of Broadbent's theories were able to account for results showing some level of semantic processing of unattended stimuli. Treisman (1960) offered a modified version of Filter Theory, Attenuation Theory, which remained in the camp of early selection models as selection was still thought to occur early in the processing stream. However, she suggested that rather than completely block further processing of information in the unattended channel(s), the filter in Broadbent's model attenuated information in unattended channels. Thus, if stimuli of high personal relevance (e.g., participants' name) or salience was in the unattended channel, it would still have the opportunity to reach awareness.

While Treisman's modification of Broadbent's theory still maintained early selection, subsequent modifications were more extreme in that they eliminated any perceptual filter entirely, and instead placed a filter at later post–perceptual stages. One of the first late selection models was put forth by Deutsch and Deutsch (1963). The authors argued that experiments which showed that participants were unable to report information from an unattended stream, may have been reflective of a failure of these stimuli to enter memory or to contribute to deliberate responses, rather than suggesting that these stimuli failed to receive full perceptual and semantic processing. Thus, in late selection models it was suggested that all stimuli were processed in parallel for all processing stages (distinguishing physical attributes and extracting semantic information); however, only the most relevant stimuli would be entered into memory or contribute to responding. This model was able to accommodate failures of selective attention (irrelevant information reaching awareness) as it suggests that irrelevant stimuli are also processed to the semantic level, and if they were salient enough they could enter memory or aid in deliberate responding. Thus, similar to Treisman's account, the model proposed by Deutsch and Deutsch (1963) suggested that the saliency of the irrelevant stimuli holds a strong role in determining if such stimuli will contribute to responding. However, in contrast to Treisman's model which includes a filter that attenuates non–salient irrelevant stimuli, the model by Deutsch and Deutsch suggests that all stimuli are processed to the same degree, however, only the most salient will enter into memory and contribute to responding.

While the late selection models were able to account for failures of selective attention, they were not able to account for emerging research which demonstrated strong success of selective attention, even when the irrelevant stimuli were highly salient. One such example is the phenomenon of inattentional blindness. Inattentional blindness refers to instances in which individuals fail to notice unattended objects or events in visual images or scenes. One of the most famous examples of inattentional blindness was provide by Simons and Chabris (1999). In this study, participants were shown a video of people playing basketball and were asked to count the number of passes made by one of the teams. During the video, a person dressed as a gorilla would run across the screen while beating his/her chest. Interestingly, participants often failed to report seeing this event. This particular example of inattentional blindness is important, as it shows that even highly salient stimuli can fail to be detected. Again, it may be argued that perhaps the gorilla was processed, but failed to enter memory, however given the salience of the gorilla this seems unlikely (Simons, 2007).

Given the mixed evidence in support of the early and late selection models, Kahneman and Treisman (1984) noted that popularity of the different models may have in part been determined by the prevailing paradigms of the times. Specifically, they noted that while the early selection view dominated in the 1950s and 1960s, the late selection models dominated in the 1970's and 1980. Furthermore, during the popularity of early selection models, typical paradigms involved providing participants with large amounts of information in both relevant and irrelevant streams, such as in dichotic listening paradigms. In contrast, during the popularity of late selection models, paradigms involved presenting participants with less information in both the attended and non–attended streams, and thus these paradigms supporting early selection models involved much more filtering than those supporting late selection models. As such, Kahneman and Treisman (1984) suggested that in fact a resolution in the long standing debate between early and late selection may not be attainable, as research supporting the different models may have been examining different aspects of attention.

Resolving the early vs late selection debate: Perceptual Load Theory

Building from Kahneman and Treisman (1984), Lavie agreed that the particular paradigms used to assess selective attention may indeed be critical in determining if the results would support early or late selection models. However, unlike Kahneman and Treisman (1984), she did not believe that the debate focused on different attentional mechanisms. Instead she proposed PLT, which was capable of explaining the discrepancies in studies which supported early and late selection models. Specifically, it was suggested that a high PL (hereafter, HL) was necessary in order for selective attention to be successful. This theory was able to explain why early studies, which could essentially be considered HL studies (e.g., dichotomous listening), were able to provide support for early selection models as selective attention was successful.

However, studies that supported late selection models (e.g., Flanker task, Eriksen & Eriksen, 1974; Stroop task, Stroop, 1953) typically used tasks with lower PL (hereafter, LL).

In her now seminal papers (Lavie and Tsal, 1994; Lavie, 1995), Lavie lays out PLT, which offers the potential for a resolution between the early versus late selection models of selective attention debate. The theory retains the assumption of capacity limitation that characterized early selection models, as well as the automatic and mandatory processing that characterized late selection models. Specifically, PLT suggests that there exists a capacity limitation in terms of processing resources, and furthermore, that there is mandatory and automatic processing up to the capacity limitation, with top–down executive control mechanisms assigning priority to task–relevant stimuli based on current goals. Thus, according to Lavie, during HL conditions, processing resources will be exhausted in the processing of task–relevant stimuli, and as such no resources are spared for processing task–irrelevant stimuli, and so selective attention is successful. In contrast, during low LL conditions, processing resources are not fully exhausted by the processing of task–relevant stimuli and so there is a spill over such that task–irrelevant stimuli are processed, leading to a failure of selective attention. Thus, according to this view, HL is a necessary condition for effective selective attention, as only HL can exhaust processing resources such that no spare resources are available to process task–irrelevant stimuli.

The impact of PL in the uni–modal domain

While the concept of PL remains vague, it is typically described as increasing the amount of processing resources required by increasing either the number of stimuli that need to be processed (e.g., Lavie, 1995; Lavie & Cox, 1997), or by increasing the difficulty of the task (e.g., Lavie & Cox, 1997).   Importantly, increasing the difficulty of the task via cognitive (e.g., working memory), rather than perceptual (e.g., feature versus conjunction search, e.g., Treisman

& Gelade, 1980), manipulations seems to have the opposite effect. While increased PL decreases distractor processing, increased cognitive load increases distractor processing. Specifically, when the cognitive load is low, selective attention leads to the selection and maintenance of task-relevant stimuli for processing, and when the PL is high, all resources are exhausted on the target information, leading to decreased distraction. However, maintenance of current goals begins to falter under conditions of high cognitive load leading to increased perceptual processing of distractor information For a more detailed discussion see Lavie, Hirst, de Fockert, & Viding, 2004). The current dissertation focused exclusively on increased PL under conditions of low cognitive load.

Lavie (1995) described three studies which provided support for PLT in the visual domain. All three of these studies used variations of a response competition paradigm (Eriksen & Eriksen,1974) in which one of two targets are centrally presented alongside peripheral distractors, and participants are asked to report which of the two predefined targets was present on a given trial. The distractor could be congruent, incongruent, or neutral with respect to the target response. In Experiment 1 (Lavie, 1995) the targets were defined as the centrally presented letters *x* or *z*, and distractors were the peripherally presented letters *X*, Z, or *P*. Although all targets were central as compared with the peripheral distractors, the targets could be presented at one of six central positions which were classified as center (1.4 degrees from distractor), intermediate (2.1 degrees from distractor) or edge (2.9 degrees from distractor). The distractors had an equal chance of being congruent (X when the target was x or Z when the target was z), incongruent (X when the target letter was z, or Z when the target letter was x) or neutral (P when the target was either x or z) with respect to the target response. Based on this design, distractor compatibility effects were indexed by increased reaction time or error rates in cases of incongruent relative to neutral trials (referred to as interference effects), and decreased reaction time or error rates in cases of congruent relative to neutral trials (referred to as facilitation effects). PL was manipulated by the number of centrally presented items. In the LL condition, the target was presented on its own, while in the HL condition the target was presented among five non–target letters. As predicted by load theory, under conditions of HL distractor interference effects were significantly reduced relative to the LL condition. Importantly, although decreased separation between target and distractors increased overall interference effects such that interference was greater for more eccentric targets, this effect was independent of the PL, suggesting that increased separation in and of itself is not sufficient in reducing/eliminating distractor interference effects, as all target–distractor distance pairings led to interference in the LL condition.

In contrast to the study discussed above, the remaining studies reported by Lavie (Experiments 2a, 2b and 3, 1995) manipulated PL without a concomitant change in the display. That is, while high PL was conceptualized by an increased number of stimuli in Experiment 1, in Experiments 2 and 3, PL was conceptualized by an increase in task demands in the HL condition. In Experiment 2a and 2b and 3, a go/no–go task was used such that participants made a response based on the detection of a feature (e.g., colour; LL) or based on the detection of a conjunction of features (e.g., colour and shape; HL) with conjunction detection requiring more perceptual processing (cf. Treisman & Gelade, 1980). As in Experiment 1, Experiments 2 and 3 provided support for PLT in that target interference effects were reduced/eliminated in high compared with LL conditions. This series of experiments demonstrated the utility of PLT, under various conceptualizations of PL including those which increased the demands on processing resources by increasing the number of stimuli requiring processing (Experiment 1), or by increasing the demands of the task while holding the number of stimuli to be processed constant (Experiments 2 and 3).

Subsequent to Lavie's seminal paper, the elimination of distractor processing under HL conditions using response competition paradigms have been replicated (e.g., Lavie and Cox, 1997; Lavie and de Fockert, 2003, Lavie and Fox, 2000). As noted by Beck and Lavie (2005) many of these studies examined distractor processing almost exclusively based on paradigms employing peripheral distractors. Given that central distractors may led to more interference than peripheral distractors, Beck and Lavie (2005) thought it would be important to determine if PLT would extend to central distractors. As such the authors modified the paradigm used by Lavie (1995) such that distractor letters could either be presented in the periphery outside of the target display circle, or at fixation in the center of the circle. The results of the study showed that while central distractors did in fact led to greater interference than peripheral distractors, modulation of interference by PL was equivalent for both types of distractors. Specifically, the difference in cost of distractor compatibility for the HL and LL conditions was 52 ms for peripheral distractors and 53 ms for central distractors. The results of this study show that central distractor processing also depends on available resources, thus extending the findings of Experiment 1 in Lavie's (1995) PLT to central distractors.

While much of the research on visual PL has used a response competition paradigm, other paradigms have also been used. Behavioural paradigms including implicit learning (e.g., Jiang & Chun, 2001), negative priming (e.g., Lavie & Fox, 2000) and inattentional blindness, (e.g., Cartwright, Finch & Lavie, 2007), as well as neuroimaging paradigms examining brain activity during low and HL (e.g., Reese, Frith & Lavie, 1997; Handy & Mangun, 2000) have all provided support for PLT. That load theory has been tested using various measures of distractor processing (both implicit and explicit) is important, as one critique of the early selection models was that it was unclear if distractors were in fact processed at some level, but may not have been processed enough to impact overt behaviour (typically reaction time and error rate measures; Deutsch and Deutsch, 1963). Thus, studies that have shown the elimination of distractor processing under HL using implicit measures (e.g., Jiang & Chun, 2001; Lavie & Fox, 2002; Cartwright, et al., 2007) and neuroimaging methods (e.g., Reese, Frith and Lavie, 1997; Handy and Mangun, 2000) provide strong support that high visual load leads to early selection in which distractors do not enter awareness.

While there is much evidence in support of PLT, it is not without critique (e.g., Fournier, Brown & Winters, 2002; Tsal & Benoni, 2010). One concern with PLT is that much of the research has been conducted using a set size manipulation and thus the observation of decreased distractor processing in the HL condition may be driven primarily by changes in the visual display (Benoni & Tsal, 2012: see also Benoni and Tsal, 2010; Tsal and Benoni, 2010a, 2010b; Wilson, Marois and MacLeod, 2011). Specifically, according to a dilution account, the presence of non–target items in the HL display may dilute the representation of the distractor item and thus reduce its impact on target processing. In a series of studies, Tsal and Benoni (2010) manipulated PL as well as dilution to determine their relative impact on distractor processing. In all experiments the LL and HL condition were similar to Laive’s Experiment 1 (1995) in which she used a set size manipulation. Specifically in the LL conditions the target was centrally presented with a single peripheral distractor, while in the HL condition 5 non–target items were also centrally presented alongside the target. In all experiments a LL high dilution condition was added. In this condition the target was always presented with five non–target items however various manipulations were used to increase the efficiency of the target search such that this condition represented a LL processing condition. Across all experiments, distractor interference effects were smaller in the LL high dilution condition compared with the LL condition, despite no overall differences in processing efficiency in either the RT or error rate data. More importantly, in all experiments there was evidence for increased distraction in the HL condition, compared with the LL high dilution condition. The authors suggest that these results provide strong support that dilution, and not PL, impacts distractor processing. The extent to which dilution can fully account for the findings of PLT are currently under debate (see commentary between Tsal & Benoni, 2010a, b, and Lavie & Torralbo, 2010). Furthermore, evidence for PLT has also been found without manipulations of set size (e.g., Lavie, 1995, Experiment 1 and Experiment 2). However, given concerns regarding set size manipulations, the current dissertation did not employ changes to set size in any of the PL manipulations in order to avoid potential dilution effects.

The research reviewed thus far has been conducted exclusively in the visual modality, and while the body of literature examining load theory in the visual domain is much more extensive than the complementary investigation of PLT in the auditory domain, available data provide broad support for the extension of PLT to the auditory domain using similar conceptualizations of PL. For example, Alain and Izenberg (2003) found support for PLT in the auditory domain by manipulating task demands in a LL and a HL condition using a feature and conjunction task, respectively. The authors examined the impact of auditory attentional load on the mismatch negativity (MMN) ERP component, which is usually produced by infrequent/deviant auditory stimuli, at attended versus unattended locations (see Naatanen, Paavilainen, Rinne, & Alho, 2007, for review). Participants were presented with a selective listening task in which an auditory stream of tuned and mistuned stimuli were presented to each ear, with one ear designated as attended and the other unattended.   Behavioural results showed increased RT and errors on the conjunction relative to the feature task, confirming that their manipulation of PL was indeed successful. Electrophysiological results showed that the MMN to deviants in the unattended stream was significantly reduced in the high (conjunction) relative to the low (feature) load conditions, demonstrating that increased attentional demands decreased the processing of sounds in the unattended stream.

A second conceptualization of PL in the visual domain is an increase in visual set size (increased number of stimuli that require processing). Manipulating set size is arguably more difficult in the auditory domain, as such, rather than manipulating the number of stimuli presented in a given space, researchers have manipulated the number of stimuli presented over a given time.   For example, in an early study by Woldorff, Hackely and Hillyard (1991) the authors present participants with streams of auditory input to both ears and asked them to attend to one ear only. The PL of the task was manipulated by having either a slow inter–stimulus interval (ISI: LL conditions) or a fast ISI (HL condition). In line with PLT, the authors found that the fast ISI significantly reduced MMN to deviant tones in the unattended stream. While this study suggests that load does impact auditory selective attention, the authors did not provide any behavioural results which confirmed that the fast ISI did indeed increase task demands (although see Neelon, Williams and Garell, 2011, for a similar findings in which behavioural trends were in the correct direction). Using a similar paradigm, however, Gomes, Barrett, Duff, Barnhardt, and Ritter (2008) failed to provide support for PLT. Here participants monitored one of two channels defined by pitch for the occurrence of lower intensity tones while ignoring the other channel, which also contained both low– and high–intensity tones. The PL of this task was also manipulated by changing ISI and the processing of stimuli in the unattended channel was indexed by the onset latency and amplitude of various evoked response potentials, including the negative difference (Nd) wave. The Nd is thought to be indicative of a distinction between processing of attended and unattended stimuli (see Hansen & Hillyard, 1980). The results showed no electrophysiological evidence of increased processing of distractor tones under low (slow ISI), compared to high (fast ISI) PLs. However, in this study there were also no behavioural effects of ISI, making any claims about PL difficult as PL effects are contingent on the load manipulation increasing task difficulty in the HL condition.

Taken together, the review above suggests that there is much support for PL in the uni–modal visual literature. While the findings in the auditory domain are somewhat mixed, there is some preliminary support for the application of Lavie's (1995) PLT to the auditory domain.

Contrasting the effects of sensory degradation and perceptual load on selective attention

In an influential paper by Norman and Bobrow (1975) the authors make a distinction between two types of processing; processing that is limited by available resources (capacity limited) and processing that is limited based on the quality of incoming information (data limited). Importantly, they suggest that data limited processing cannot be compensated for by applying more resources, and thus a data limit cannot led to a capacity limit. In an important paper by Lavie & de Fockert (2003), the authors apply the notion of data and capacity limited processing to selective attention in order to further support PLT by stating that PL effects are not the same as the effects of general task difficulty in which the task demands increase due to factors other than the required perceptual processing. Specifically, they argue that both PL (capacity limited) and SD (data limited) led to performance decrement, typically indexed by increased reaction times (RT) and increased errors. However, they speculate that since capacity limits require all resources to be allocated towards the target task, under these conditions distractor processing should decrease. On the other hand, the effects of data limits on distractor processing were less clear, however they speculated that due to longer RTs *and* the inability for additional resources to resolve data limited processes, there may be increased distraction in the SD condition, as supported by previous literature (Eriksen & Schultz, 1997; Navon, 1989). Lavie and de Fockert (2003) provided empirical support for a dissociation of data and capacity limited processing on distractor effects by designing a series of studies that included a LL condition, a HL condition and an SD condition. In all experiments, a set size manipulation was used to create the HL condition. That is to say, in the LL condition participants were presented with a single target stimulus and a single peripheral distractor. In the HL condition participants were also presented with a single target and a single peripherally presented distractor, however in addition to the target, five non–target items were also presented. The SD condition was similar to the LL condition with the exception that in Experiment 1 the target letter was half the size of the target letters used in the other two conditions and had a reduced contrast intensity. In Experiment 2, the SD condition was similar to Experiment 1, however in addition the duration of display was reduced by half, and a mask was presented at target locations immediately following target presentation. Finally in Experiment 3, the SD manipulation was created by having the targets placed at greater eccentricity than they were in the LL and HL conditions. Across all three studies, HL conditions decreased distractor effects relative to the LL baseline, while SD conditions increased distractor effects relative to the LL baseline. This finding is in line with Experiment 1 of Lavie's seminal paper (1995). In that experiment, in addition to the typical load manipulation of increased non–target items, the eccentricity of the targets were also varied (across both LL and HL conditions), and while HL conditions showed reduced distraction compared to LL conditions for all target eccentricities, overall distractor effects increased with the eccentricity of the target presentation. Together, these findings support the distinction between data and capacity limited processing put forth by Norman and Bobrow (1975) and suggest that they led to different effects on selective attention.

In direct contrast, a follow up study conducted by Benoni and Tsal (2012) using a similar design did not find any differences in the patterns of change in distractor processing from LL to either HL or SD conditions. In Experiment 1, Benoni and Tsal replicated Experiment 1 of Lavie and de Fockert (2003), however they included an additional condition which they termed SD high dilution, as in this condition there were non–target items present alongside the target that had the potential to dilute the salience of the distractor item. In this condition, in addition to decreasing the size and contrast intensity of the target letter in the SD condition, 6 non–target letters were presented. In this experiment the results of Lavie and de Fockert were replicated, however the SD high dilution condition led to decreased distractor processing despite this condition being considered a data limited condition. In Experiment 2, Benoni and Tsal include the LL, HL, and SD high dilution conditions from Experiment 1, however they also include a new condition of LL high dilution. In this condition the target letter was presented among the 6 non–target letters, however to ensure this condition was in fact LL, the target letter was underlined making target search more efficient. In this study, using the LL high dilution as a baseline, the authors report increased distraction for both the HL and the SD high dilution condition. Thus in their experimental series, the authors provide strong support that the effects observed by Lavie and de Fockert were driven by dilution in the LL and the SD conditions, rather than PL.

While these studies provide conflicting evidence, looking at studies that have manipulated only PL or only SD does provide support for a different impact of data and capacity limits on selective attention. As reviewed above, there is much literature to suggest that HL conditions led to decreases in distractor processing, including studies that have not used a set size manipulation (e.g., Lavie, 1995, Experiments 2 & 3). In terms of SD there is evidence that degrading the target leads to increased distraction (Kane, May, Hasher, Rahhal, Stoltzfus, 1997; Eriksen & Schultz, 1997; Navon, 1989).

Looking at the studies that have directly contrasted data and capacity limits (Lavie & de Fockert, 2003; Benoni & Tsal, 2012), different manipulations were used to promote HL and SD. Specifically, HL was manipulated via a set size manipulation and SD was manipulated by size, contrast and duration reductions as well as greater eccentricity of the target. While these manipulations are those that are typically used to produce HL and SD conditions, there have been instances in which researchers have used typical SD manipulations, including duration reductions (e.g., Handy, Soltaini & Mangun, 2001) similar to those reported in Lavie and de Fockert, (2003) as PL manipulations, and have found decreased distractor processing. Thus the distinction between data and capacity limited conditions is not entirely clear. In fact, in the seminal paper by Norman and Bobrow, (1975) the authors state that in all tasks, once a capacity limit has been reached the task becomes data limited as performance is no longer dependent on the capacity of the perceptual system since the required processing exceeds that which is available, rendering performance which is instead determined by the incoming data itself . This provides theoretical support that capacity and data limits rest on a continuum, and should be able to be achieved using a single manipulation that places successively greater demands on available resources.

Given the conflicting evidence, and the vagueness as to what constitutes data and capacity limited conditions, the question still remains whether data and capacity limits produce contrasting effects on selective attention.

Individual differences in attentional control & selective attention

One final potential contributor to the success or failure of selective attention is individual differences (ID) in attentional control. The notion that individuals vary in their ability for selective attention has long been recognized and has received early empirical support (e.g., Tipper & Baylis 1987; Mihal, Barrett and Gerald 1976). Today there exists a large body of evidence demonstrating individual differences in the ability for uni–modal distractor processing across a variety of tasks including inattentional blindness, (e.g., Hannon & Richards, 2010; Richards, Hannon, & Derakshan, 2010; Simons & Jensen, 2009; Seegmiller, Watson & Strayer 2011) the visual Stroop task (e.g., Kane & Engle, 2003), inhibiting saccades to peripheral stimuli (e.g., Unsworth, Schrock, & Engle, 2004; Kane, Beckley, Conway & Engle, 2001), dichotic listening paradigms (e.g., Conway, Cowan & Bunting, 2001; Colflesh & Conway, 2007), and, attentional blink tasks (e.g., Martens, Munneke, Smid, & Johnson, 2006; Martens & Johnson, 2009; Martens & Valchev, 2009; Feinstein, Stein, Castillo & Paulus, 2004; Mclean & Arnell, 2011).

While this body of work suggests robust variability in individuals' selective attention abilites, very little research has assessed how such ID might interact with other factors affecting selective attention, such as PL and SD. To my knowledge only one study has jointly considered ID in selective attention and PL effects in non–clinical populations. Forster and Lavie (2007) used the Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982) to assess ID in distractibility in everyday life. Using a median split of the scores on the

CFQ, they divided participants into low and high distractibility groups. Their results showed that the reduction typically seen in high relative to LL conditions was smaller for individuals in the low distractibility group. Furthermore, this effect was driven by group differences in the LL condition. Specifically, in the LL condition the low distractibility group showed smaller distractor interference effects than the high distractibility group, however distractor interference effects were the same for both groups in the high distractibility condition. The finding that both groups performed similarly during the HL condition provides support for high PL as a capacity limitation. Capacity limitations require that all processing resources are exhausted. In line with this notion, individuals in the low and high distractibility group would not be expected to (and did not) show differences in distractor effects in the HL condition, as there would be no spare resources to ‘control’ in this condition, rendering ID in attentional control meaningless.

While Forster and Lavie (2007) provided evidence for an interaction of ID in attentional control and PL, there are some limitations in the design of their study. This study used a self–report measure of distractibility, and so there is no objective evidence supporting the association between distractibility and PL. In addition, a median split was used to create the group, which is not ideal as this procedure dichotomizes a continuous variable (Field, 2009), thus a correlation measure may have been more appropriate. These factors may have contributed to the absence of any effects of distractibility in the HL condition. Considering this is the only study thus far to assess the relationship between ID in attentional control and PL, it will be important to replicate these findings in the absence of the above mentioned limitations.

The results of Forster and Lavie (2007) suggest that when capacity limitations are not reached, individual differences in attentional control impact distractor processing. Given that SD does not reflect a capacity limitation, then it may be expected that ID in attentional control will impact selective attention in both intact and degraded conditions. However, this effect is dependent on the mechanism that leads to increased distractor processing in degraded conditions. Lavie and de Fockert (2003) suggest that the increased distractor effects observed in the SD condition were due to the longer processing time required for this condition relative to the LL condition, thus creating a larger time–window in which distractor could influence target processing. However, as pointed out by Benoni and Tsal (2012), this should also be true in the HL case. Instead Benoni and Tsal suggest that as task difficulty increases (due to either a data or a capacity limit) there are fewer processing limits available for inhibiting distractor processing. Under Lavie and de Fockert's explanation, we may expect to see an impact of individual differences in attentional control under SD conditions, as participants would have to prevent distraction for longer durations in the SD condition. However, under Benoni and Tsal's explanation, both HL and SD led to consumption of resources, and thus we may not expect to find any impact of individual differences here.

To summarize, while limited, there is some evidence to suggest that ID in attentional control interact with PL, with the impact of ID emerging only in LL conditions (Forster & Lavie, 2007). However, given the choice of a self–report measure of daily distractibility, and the use of a course method to differentiate individuals on distractibility (median split), the results of this study need to be interpreted with caution. In addition, this study was carried out in the unimodal visual domain, and so it remains to be determined if similar effects of ID in attentional control would be observed in cross–modal situations. Similar interactions between ID in attentional control and SD may exist, but to date have not been tested. Furthermore, no study has directly contrasted the joint effects of ID in attentional control and SD and PL on selective attention. Such a study has the potential to provide further support for the notion of dissociation between

SD and PL effects as data and capacity limits respectively, if there are different effects of ID in these conditions.

The Attentional Network Task

One commonly used objective measure of attentional control is the Attentional Network task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002), which provides reliable objective measures of alerting, spatial orientating and executive control aspects of attention at the individual level. As noted by Macled, Lawrence, McConnell, Eskes, Klein & Shore (2010) the appearance of the ANT in over 65 empirical articles suggests that the ANT is widely considered to be a valid measure of attentional abilities in the domains of alerting, orienting and executive control. In the current dissertation, the executive control aspect of the ANT was used as a measure of individual attentional control ability. This measure has been shown to have the greatest reliability of the three attentional measures provided by the ANT (r = .77, p < .05 Fan, Wu, Fosella & Posner, 2001; see also Fan et al., 2002; Greene, Barnea, Herzberg, Rassis, Neta, Raz & Zaidel, 2008; Roberts, Summerfield & Hall, 2006).

The ANT is a reaction time task that is composed of both flanker (Eriksen and Eriksen, 1974) and cueing paradigms (Posner, 1980), which are accepted measures of attentional control and alerting respectively. In the ANT, participants are presented with a central arrow that is flanked by two arrows on either side. The arrow display can be presented either above or below a fixation point. The participants are asked to report the direction in which the central arrow points. The flanker arrows can either point in the same direction (congruent trials) or in the opposite direction (incongruent trials) as the center arrow, or else have no direction (straight lines: neutral condition). Prior to the presentation of the arrow display, participants are presented with one of four possible cue types. In the no cue condition, the participants are not provided with any cue prior to the arrow display. In the center cue condition, a cue is presented in the center of the screen. Given that the arrow display always appears either above or below fixation, the central cue is considered spatially uninformative. In the double cue condition, a cue is presented both above and below fixation. Again, since the double cue cannot predict the location of the arrow display this is also considered a spatially uninformative cue, however given the appearance of a cue at two locations, this cue is thought to be more alerting than the no cue. Finally, in the single cue condition, a cue appears either above or below fixation and is 100% predictive of the subsequent target display location, rendering this the only spatially informative cue.

Measures of the three aspects of attention are obtained via subtraction of the different conditions. Specifically spatial orienting is assessed via subtraction of the participant's performance (both RTs and error rates) on the single cue from the central cue. Alerting is measured via subtraction of the double cue from the no cue condition. Most relevant to the current dissertation is the measure of executive control which is obtained via the subtraction of performance on congruent trials from performance on incongruent trials.

While the original version of the ANT is a visual test, Roberts et al. (2006) created an auditory analogue of the ANT to assess the impact of presentation modality on the three aspects of attention measured by the ANT. Critical to the current dissertation, they found that executive control measures in the auditory and visual versions of the ANT yielded effects that were similar in magnitude (mean RT cost of 118ms in vision and 145ms in audition, $t(39) = -0.4$, $p = .66$) and were significantly correlated ($r = .33$, $p < .05$). This led the authors to suggest that executive control may be supramodal. Regardless of whether executive control is supramodal or modality specific, the significant correlation suggests that participants that have high attentional control in vision, also have high attentional control in audition. Thus, in the current dissertation, in line with Roberts and colleagues (2006) suggestion that the visual ANT is sufficient for assessing executive control abilities across modalities, the traditional visual ANT developed by Fan et al. (2002) was used in Experiments 1 and 2 to measure individual differences in uni–modal attentional control. While there is some correlation between the visual ANT and its auditory analogue, the correlation is not perfect, and thus we may expect a modality asymmetry to arise. However, it is important to stress that although the current dissertation is employing a visual test to assess attentional control in both the visual and the auditory modality, this does not imply an assumption of shared resources across modalities. Instead I was interested in whether uni–modal attentional control interacts with PL and SD to impact cross–modal selective attention. Given the reliability of the ANT and the significant correlation between performance on the executive control aspect of the visual ANT and the auditory analaogue (Roberts et al., 2006), I used the visual ANT as a measure of attentional control in both the auditory and visual modalities.

Current experimental Series

The literature reviewed thus far has focused on the effects of PL and SD on selective attention in the uni–modal domain. The current dissertation seeks to evaluate the effects of these factors on cross–modal selective attention. Literature on the effects of PL and SD on cross–modal selective attention will be reviewed in the introductions of Chapters 2 and 4 and, Chapters 3 and 4, respectively.

Experiment 1 sought to evaluate the role of PL on cross–modal distractor processing. As will be discussed in detail in Chapter 2, the current literature reports mixed findings. Specifically, while some studies support PLT such that cross–modal distractor processing is reduced under HL conditions (e.g. Macdonald & Lavie, 2011; Mulligan, Duke, & Cooper, 2007;

Toro, Sinnett & Soto–Faraco, 2005; Haroush, Hochstein & Deouell, 2009; Dyson, Alain & He, 2005, Experiment 2; Sinnett, Costa, & Soto–Faraco, 2006, Experiment 1; Klemen, Buchel & Rose, 2009), others studies report either no difference in distractor processing between LL and HL conditions (e.g., Parks, Hilimire, Corballis, 2011; Muller–Gass, Stelmack and Campbell, 2006; Rees, Frith, and Lavie, 2001, Experiment 2; Vroomen, Driver and De Gelder, 2001) or report increased distraction in HL conditions (e.g., Tellinghuisen and Nowak, 2003; Jacoby, Hall and Mattingley, 2012). These mixed findings may be in part due to some studies evaluating the impact of auditory distractor on visual target processing, and others of visual distractor on auditory target processing. As suggested by Jacoby and colleagues (2012), the target and distractor modality may play a role in determining the impact of PL on distractor processing. In addition to the mixed findings in this literature, only two studies have assessed cross–modal distractor processing using compatibility effects (Tellinghuisen and Nowak, 2003; Vroomen, Driver and De Gelder, 2001), which is how PLT is typically examined in the uni–modal domain. As such, Experiment 1 seeks to explore the role of PL on cross–modal distractor processing, with some important improvements over previous research. First, PL will be manipulated without the use of a change in set size from LL to HL to avoid potential dilution confounds (e.g., Tsal & Benoni, 2010). Second, both audition and vison will serve as the target and distractor modality, so that the impact of attended modality can be evaluated. Third, PL effects will be assessed using measures of facilitation (congruent vs. neutral), interference (incongruent vs. neutral) and overall distraction (incongruent vs. congruent). Fourth, using the neutral trials, a measure of processing efficiency will be included to determine whether any difference in distractor effects across modalities can be accounted for based on differences in the relative processing efficiency of each modality (Mordkoff & Yantis, 1991). Finally, in addition to the main task, participants will complete the ANT task (Fan et al., 2002) and the executive function scores on the ANT will be correlated with distractor effects in the main task.

Experiment 2 sought to evaluate the role of SD on cross–modal distractor processing. While in the uni–modal literature the mechanism that causes increased distraction in the SD compared to the LL conditions is unclear, there is strong support in the cross–modal domain that degradation of the target modality leads to a shift/widening of attentional scope to include the distractor modality. As will be discussed in greater detail in Chapter 3, in an important paper by Ernst and Banks (2002), the authors show that when information is degraded in one modality, there is a re–weighting of sensory input in favour of the non–degraded modality, which in selective attention paradigms is typically the distractor modality. Re–weighting of sensory modalities in favour of the non–degraded modality cannot occur in the case of SD in uni–modal conditions, and thus it is important to assess the impact of SD on cross–modal selective attention. While there is some support in the cross–modal domain that interference by audition on visual target processing increases when the visual modality is degraded (Yuval–Greenberg & Douelle, 2009), this study did not assess the impact of vision on auditory target processing when the auditory targets were degraded. As such there is need for further investigation of the impact of SD on cross–modal selective attention.

Experiment 2 consists of two studies. In the first (2a), various methods of stimulus degradation and their resultant impact on processing efficiency in both the visual and auditory modality were assessed. Based on the results from this study, the SD manipulation for Experiment 2b was selected based on which manipulation led to similar decrements in processing efficiency in both modalities. In Experiment 2b the impact of degrading the target modality on selective attention was assessed using compatibility measures, and as in Experiment

1, neutral trials were included to provide measures of facilitation, interference and overall distraction. Furthermore, as in Experiment 1, a processing efficiency score was calculated to assess its role on distraction, and the ANT was completed to provide an investigation of the influence of individual differences in attentional control on cross–modal distraction under degraded conditions.

Experiment 3 sought to directly contrast the effects of PL and SD in a single experiment, to determine if data and capacity limits would led to differing effects on cross–modal selective attention. The only two studies to do so (Lavie & de Fockert, 2003; Benoni & Tsal, 2012), have found conflicting results, and have been carried out in the uni–modal domain. Furthermore, these studies have used different manipulations to create the HL and SD conditions, thus introducing potential confounds into any resultant comparisons. Experiment 3 in the current dissertation directly compared PL and SD effects on cross–modal distractor processing within a single experiment, and used a single manipulation to promote data and capacity limited processing. As in Experiments 1 and 2, Experiment 3 employed a compatibility measure of selective attention, however neutral trials were not included and thus only the overall distraction score (incongruent – congruent) was assessed. However, in addition to the compatibility score, Experiment 3 also included a detection measure of selective attention. As reviewed, early selection theories of selective attention (e.g., Broadbent, 1958) suggest that all stimuli are processed at the perceptual level, but only some are selected for further semantic processing. Thus to rule out the possibility that distractor effects were present but did not impact compatibility data which relies on semantic processing, the detection measure was included.

I was the main contributor to each experiment. I conceptualized, designed and programmed each study. I collected, analysed and interpreted the results, and I wrote all resultant manuscripts.

Chapter 2: Experiment 1. The impact of PL on cross–modal distractor processing

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Abstract

Visual distractor processing tends to be more pronounced when the perceptual load (PL) of a task is low compared to when it is high (perpetual load theory (PLT); Lavie, 1995). While PLT is well established in the visual domain, application to cross–modal processing has produced mixed results, and the current study was an attempt to improve previous methodologies. First, we assessed PLT using response competition, a typical metric from the uni–modal domain. Second, we looked at the impact of auditory load on visual distractors, and of visual load on auditory distractors, within the same individual. Third, we compared individual uni– and cross–modal selective attention abilities, by correlating performance with the visual Attentional Network Test (ANT). Fourth, we obtained a measure of the relative processing efficiency between vision and audition, to investigate if processing ease influences the extent of distractor processing. Although distractor processing was evident during both attend–audition and attend–vision conditions, we found that PL did not modulate processing of either visual or auditory distractors. We also found support for a correlation between the uni–modal (visual) ANT and our cross–modal task but only when the distractors were visual. Finally, although auditory processing was more impacted by visual distractors, our measure of processing efficiency only accounted for this asymmetry in the auditory high load condition. The results are discussed with respect to the continued debate regarding the shared or separate nature of processing resources across modalities.

Introduction

Our daily sensory environment is complex, and more often than not provides information from multiple sources in multiple sensory modalities. Selective attention is thought to be one mechanism that selects goal–relevant (target) stimuli for further processing while inhibiting the processing of goal–irrelevant (distractors) stimuli. While selective attention is important in preventing sensory overload, it is not always successful (e.g., Eriksen & Eriksen, 1974; Gatti & Egeth, 1978; Stroop, 1935). Lavie and colleagues (Lavie & Tsal, 1994; Lavie, 1995) have suggested that one factor in determining the success of visual selective attention is the perceptual load (PL) of the task. Specifically, she suggested that perceptual resources have a limited capacity, with an obligatory use of all possible resources. Thus, when the PL of the task is low, not all resources are used on target processing, and thus spill over to distractor processing. Conversely, when the PL is high, all resources are exhausted on target processing meaning that distractors are not processed, and thus interference with target processing is reduced.

Much of the early support for perceptual load theory (PLT) came from assessing the impact of PL on the flanker task (Eriksen & Eriksen, 1974), which consistently demonstrated that flankers disrupt target processing to a greater degree when the perceptual demands of the task were low (e.g., Lavie, 1995; Lavie & Cox, 1997; Lavie & de Fockert, 2003, Lavie & Fox, 2000). However, recently, more diverse methods have been used to demonstrate the effects of PL on distractor processing. Behavioural paradigms including implicit learning (e.g., Jiang & Chun, 2001), negative priming (e.g., Lavie & Fox, 2000) and inattentional blindness, (e.g., Cartwright, Finch & Lavie, 2007), as well as neuroimaging paradigms examining brain activity to distractors during low and high load (e.g., Handy & Mangun, 2000; Reese, Frith & Lavie, 1997), have all provided support for PLT.

While there is generally broad agreement for the role of PL for processing within the visual modality and, to some extent within the auditory modality (Francis, 2010; although see Gomes, Barrett, Duff, Barnhardt & Ritter, 2008 and Murphy, Fraenkel, & Dalton, 2013), the role of PL for processing between modalities is less clear. Some researchers propose that perceptual resource capacity limitations arise at the modality level (e.g., Duncan, Martens and Ward, 1997; Treisman & Davies, 1973; Wickens, 1980; Wickens, 1984), others suggest that such limitations arise at a supramodal level (e.g., Broadbent, 1958; Kahneman, 1973), and more recently some authors suggest that perceptual resources are coordinated across modalities and so the relationship with factors like PL might be dynamic (e.g., Driver & Spence, 1998; Driver & Spence, 2004). If resource limitations arise at the modality level such that resources are completely independent across modalities (e.g., Treisman & Davies, 1973), then PLT should not apply across modalities, and PL should not influence cross–modal selective attention. If resource limitations arise at the supramodal level such that resources are completely interdependent (e.g., Broadbent, 1958), PLT should apply across modalities, and the effects of PL on selective attention should be similar in the cross–modal and within–modal domains. Predictions are less clear under the assumption of coordinated resources across modalities, however it may be expected that certain factors such as spatial, temporal and semantic factors across modalities may increase the likelihood of a failure of selective attention across modalities (see Driver & Spence, 2004, for a review of cross modal spatial attention).

Researchers have tested PL theory across modalities using various behavioural and neurological measures, however the results have been mixed (see Table 1).

Table 1. Summary of cross–modal perceptual load studies

Load Modality	Behavioural/Neural	Distracter compatibility effects assessed	DV	Study	Perceptual load theory (PTL) support/not supported
Visual load on auditory performance	Behavioural	No	Inattentional Deafness	Macdonald and Lavie, 2011	PLT Supported
			Auditory–visual priming	Mulligan, Duke, and Cooper, 2007	PLT Supported
			Auditory statistical Learning	Toro, Sinnett and Soto–Faraco, 2005	PLT Supported
		Yes	Auditory distracter compatibility	Tellinhuisen and Nowak, 2003	PLT Not Supported: increased distracter processing during HL
	Neural	No	Auditory steady state evoked potentials	Parks, Matthew, Corballis, 2011	PLT Not Supported: No effect of PL
			Auditory mismatch negativity ERP component	See Haroush, Hochstein and Deoulle, 2010, Table 1.	
Auditory load on visual performance	Behavioural	No	Visual motion perception	Rees, Frith, and Lavie, 2001 exp 2	PLT Not Supported: No effect of PL
			Inattentional Blindness	Sinnett, Costa, and Soto–Faraco, 2006 exp 1	PLT Supported
		Yes	Emotion judgments	Vroomen, Driver and De Gelder, 2001	PLT Not Supported, No effect of PL
	Neural	No	Brain activity to visual images	Kelmen, Buchel and Rose, 2009	PLT Supported
			Visual steady state evoked potentials	Jacoby, Hall and Mattingley, 2012	PLT Not Supported: increased distracter processing during HL

Some empirical work has demonstrated support for cross modal PL effects (e.g. Macdonald & Lavie, 2011; Mulligan, Duke, & Cooper, 2007; Toro, Sinnett & Soto–Faraco, 2005; Haroush, Hochstein & Deouell, 2009; Dyson, Alain & He, 2005, Experiment 2; Sinnett, Costa, & Soto–Faraco, 2006, Experiment 1; Klemen, Buchel & Rose, 2009). Other work has failed to find support for cross modal PL effects (e.g., Parks, Hilimire, Corballis, 2011; Muller–Gass, Stelmack & Campbell, 2006; Rees, Frith, & Lavie, 2001, Experiment 2; Vroomen, Driver & De Gelder, 2001), while still other work has found results that show the opposite effects to those predicted by load theory, specifically, *increased* distractor processing under high compared to low PL (e.g., Tellinghuisen & Nowak, 2003; Jacoby, Hall & Mattingley, 2012). Given the diversity of methods used to assess the effects of PL on cross–modal distractor processing, the mixed findings in the literature may also represent methodological inconsistencies across studies with respect to the nature of the distractor effects tested, the presence of potential dilution or working memory confounds, and the use of non–orthogonal load and target modality combinations.

Regarding the nature of distractor effects, in the uni–modal domain the majority of PL studies (including the original studies of Lavie) assessed the impact of load by measuring distractor compatibility effects. The effect of PL was measured by assessing the extent to which distractors impacted on target processing due to the (in)compatibility of stimulus content. In contrast in the cross–modal domain, while many of the studies of cross–modal perceptual load have presented auditory and visual stimuli in a way to promote the interaction of resources across modalities, such as from a common spatial location and within close temporal proximity (e.g., Driver & Spence, 1998; Driver & Spence, 2004), few have imposed stimulus–based correspondence as a way to further promote interaction (e.g., see Doehrmann & Naumer 2008, for a review). Thus, the use of distractor compatibility effects in a cross–modal context is desirable as a) this is a traditional method used in the uni–modal literature, and, b) it should help promote audio–visual relationships. To the best of our knowledge, the only studies to look at PL via cross–modal compatibility effects to date were carried out by Tellinghuisen and Nowak (2003), and, Vroomen et al. (2001). Tellinghuisen and Nowak (2003) adapted the flanker paradigm used in Lavie (1995), such that distractor compatibility effects were based on the semantic relationship between written (target) and spoken (distractor) letters. Vroomen et al. (2001) manipulated distractor compatibility effects by presenting faces and voices that either did or did not portray the same emotions. The findings of these two studies, in which distractor compatibility effects were used to assess the impact of cross–modal PL, were conflicting. Tellinghuisen and Nowak (2003) found that when the target and distractor were both visual, the results were in line with PLT. However, when the distractor letter was presented in the auditory modality and the target letter in the visual modality, distractor compatibility effects were *greater* in the high load condition, demonstrating the effect of PL in the opposite direction to that predicted by PLT (see also Jacoby et al., 2012). In contrast, using emotional faces and voices, Vroomen et al. (2001) found that assessing the emotion of voices under low and high auditory PL did not differentially impact the degree of interference by the emotional face stimuli, leading the authors to conclude that PLT only applies to the within modality domain. An alternative explanation for the null findings of Vroomen and colleagues may be gleaned from more recent uni–modal visual research which suggests that PLT does not apply to highly salient stimuli such as faces (Lavie, Ro & Russell, 2003). Although these two studies found conflicting results, both suggest that PL does not modulate cross–modal distractor processing in the same way it does for uni–modal distractor processing

While the studies by Tellinghuisen and Nowak (2003) and Vroomen et al. (2001) are similar in that they both tested cross–modal distractor compatibility effects, these studies also differed with respect to the potential for dilution and working memory confounds. While Tellinghuisen and Nowak (2003) did use a relatively canonical design in assessing PLT by using distractor compatibility effects, the standard PLT paradigm has itself received criticism in its definition of PL in terms of task set size (Benoni & Tsal, 2010; Tsal & Benoni 2010; Wilson, Marois & MacLeod, 2011). Specifically, it has been suggested that the increased number of irrelevant stimuli in high PL (larger set size) conditions, leads to a dilution of the identity of the distractor. Importantly, they suggest that it is this dilution, and not PL per se, that leads to decreased distractor effects in the high load condition. While the dilution account cannot explain the results for the cross–modal condition in Tellinghuisen and Nowak (2003), as there were actually *increased* distractor effects in the high PL condition, it may have contributed to the pattern of reduced distractor processing in the uni–modal condition high PL condition. Although the study of Vroomen et al., (2001) was free of potential dilution effects, the design of this experiment required participants to complete a secondary task during the high–load condition, thus increasing working memory demands. Research has suggested that increasing working memory demands via dual–task requirements may in fact increase distractor processing (de Fockert, Rees, Frith & Lavie, 2001). Thus, Vroomen and colleagues may have increased both the PL and working memory demands of the task, although ultimately these combined effects did not modulate cross–modal distractor processing.

A final discrepancy between the two studies that have looked at cross–modal PL using distractor compatibility effects is that while Tellinghuisen and Nowak (2003) looked at the impact of visual load on auditory distractor processing, Vroomen at al. (2001) looked at the impact of auditory load on visual distractor processing. Different results may then also stem from asymmetries in the interaction between vision and audition, of which there are many (Kubovy & van Valkenburg, 2001). The role of the specific modality that serves as the target (and load) modality versus the distractor modality may be a critical factor in determining the effects of PL.

The current study had three main aims. The first aim was to assess the application of PLT to cross–modal distractor processing, by attempting to improve methodology over previous studies. In order to promote the sharing of resources across audition and vision, distractor compatibility effects were assessed by having target and distractor stimuli with temporal, spatial and semantic correspondence (for a discussion, see Wilbiks & Dyson, 2013) [2] but avoiding stimuli that have been shown to be immune to PL effect in the visual domain (Lavie et al., 2003). Furthermore, PL was assessed while eliminating the possibility for dilution or working memory confounds. Specifically, the PL manipulation in the current study did not involve a change in set size or working memory demands across high and LL conditions. We expected that, if perceptual resources are limited at supramodal level, we would find that PLT predictions hold for cross–modal distractor processing. However, if perceptual resources are limited at a modality level, we would expect to find no effects of PL.

The second aim of the current study was to further test the modality specific versus supramodal capacity limitation theories of perceptual processing in a more direct manner. Thus, in addition to the main experiment (which assessed cross–modal selective attention) participants

[2] Although Tellinghuisen & Nowak (2003) had temporal and semantic correspondence, it is unclear from the methods if there was also spatial correspondence.

also completed a standard attentional network task that assesses uni–modal visual selective attention (ANT; Fan et al., 2002). If perceptual resource capacity limitations arise at the supramodal level, then one would expect selective attention to operate similarly within and across modalities, and thus we may expect to find a correlation between individuals' performance on the main (cross–modal) task and the (visual–only) ANT. However, if the capacity limitation falls at the modality level, we might not expect to find such a correlation.

The final aim of the current study was to determine if load effects depend on the specific modality that serves as target and distractor. As such, the current experiment is the first to concurrently examine both the impact of auditory load on visual distractor processing, and, visual load on auditory distractor processing. While special asymmetric relationships between vision and audition may exist, it is important to first rule out an account of the data that is based on processing efficiency (e.g., Mordkoff & Yantis, 1991). If processing efficiency is a factor in determining the extent of distractor processing such that the more efficiently processed modality interferes more with the less efficiently processed modality, then individuals showing a greater difference in baseline auditory and visual processing should also show a greater distractor effect by the more efficient modality. If differences in the magnitude of distractor compatibility effects are observed between audition (on vision) and vision (on audition) in the absence of differences in processing efficiency across the modalities, then this provides stronger evidence for a unique relationship between sound and sight in the distribution of cross–modal PL.

Method

Participants

Forty–eight healthy adults (43 females; 38 right handed) from Ryerson University and the surrounding community participated in the study for course credit. The mean age was 19.5 years (age range 17–28 years). Twelve participants who were excluded due to errors greater than 65% on no–go trials (see below), in any single block [3] were replaced with 12 new participants. All remaining participants correctly responded to an average of 77% of no–go trials. A cut–off of 25% error rate across all conditions of the main task was also set, however, all remaining participants fell within this limit and thus no further exclusions were made.

Stimuli and Design

15 images and 15 sounds were selected, representing visual and auditory components of an object belonging to one of five categories (animals, electronics, instruments, tools or vehicles), with three possible exemplars from each category (animals; cat, cow, dog: electronics; camera, clock, phone: instruments; guitar, piano, trumpet: tools; drill, hammer, saw: vehicles; car, helicopter, plane). Auditory stimuli were taken from the Sounds and Pics stimulus set (Saygin, Dick, & Bates, 2005) and visual stimuli were taken from the Mulitmost set (Schneider, Engel & Debener, 2008). In order to attempt to equate auditory and visual responding in terms of processing efficiency (equivalent RT and error rates), visual object stimuli were further rotated 30 degrees to the left or right (Rees, Russell, Frith & Driver, 1999; Sinnett, Spence & Soto–Faraco, 2007) leading to 30 object images and 15 object sounds. Finally, in addition to the object stimuli, a neutral visual image and a neutral sound were used. The neutral visual image was created by scrambling five additional object images from the Mulitmost set and recombining them in a random order using Photoshop software (Yuval–Greenberg & Deouell, 2009). The neutral sound was created by taking five additional 100 ms sound clips taken from the Sounds and Pics stimulus set and playing them sequentially for a duration of 500 ms. A five ms onset

[3] Typically 50% is used for a cut-off in go-no-go tasks (Lavie, 1998). However, in the current study there are three buttons and so if participants were just responding based on chance they would have 67% error. Thus we used a 65% error on the go-no-go task, which is slightly conservative relative to the typical chance level cut-off.

and offset ramp was included in each 100ms sound to minimize clicking effects during sound presentation. All auditory stimuli were presented via Harman/Kardon speakers placed approximately 25 inches apart, on either side of a 15 inch Apple Studio Monitor on which visual stimuli were presented. All auditory stimuli were 500 ms and were intensity normalized with SoundEdit software. Loudness measured by a Scosche SPL 1000 sound level meter ensured that auditory stimuli were all presented at approximately 78 dB(C). All visual stimuli were fit to a five x five degree square area, and were presented centrally on a black background. Participants were seated in a quiet, darkened room approximately 57 cm from the computer monitor. All stimuli were presented using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) and participants' speed and accuracy in responding was recorded by a PsyScope Button Box.

Congruency was manipulated within a block by having the information in the auditory and visual modality represent the same object (congruent), represent a different object from a different category (incongruent: see Chen and Spence, 2010, for a discussion of semantic priming within a category), or, represent a realistic object in the attended modality while the unattended modality was a scrambled image or sound (neutral). On congruent and neutral trials, there was only one possible pairing of auditory and visual information (i.e. dog image and dog bark for congruent; object stimulus and scrambled stimulus for neutral). On incongruent trials, there were 12 possible pairings given the stipulation that the distractor had to be an object from a different modality, (i.e., dog image could be paired with any of the three exemplars from the electronics, musical instruments, vehicles or tools categories). Thus, in order to retain equivalent stimulus uncertainty in the congruent and incongruent conditions (as well as the same stimulus–response mappings), a single random pairing was used for each incongruent item, and this pairing was the same for all participants. For example, when dog was attended (in either vision or audition), it was always paired with a clock during incongruent trials.

The design of the current experiment was a within–participant 2 (attended modality: audition, vision) by 2 (PL: low, high) x 3 (congruent: congruent, incongruent, neutral) factorial design. All factors were orthogonally combined, leading to 12 conditions. Attended modality and PL were manipulated across blocks, resulting in four blocks; attend–audition– LL (AL), attend–audition – high load (AH), attend–vision – LL (VL) and attend–vision – high load (VH). In each block each object (collapsed across rotation for visual stimuli) was presented 12 times in the attended modality. Four of these presentations were paired with a congruent object in the unattended modality, four with an incongruent object in the unattended modality and four with a neutral object in the unattended modality. Given 12 presentations of each object in the attended modality by 15 objects in total, there were 180 experimental trials per block and 720 across the four blocks, leading to 60 observations per condition. Trial order was randomized per participant and block order and response mapping was counter–balanced across participants.

During each block, participants were presented with an audio–visual object at each trial followed by a printed word. Responding was based on a modified 'go / no–go' format. On 'go' trials participants were asked to decide if the printed word matched the object represented in the attended modality by pressing one button to indicate a 'yes' response and another to indicate a 'no' response. On 'no–go' trials, participants would press a third response button and forgo the verification task described above. In order to determine whether the trial required audio–visual object verification ('go') or for participants to forego the audio–visual object verification ('no–go') a discrimination task was further designed, which served as the basis of our PL manipulation. Specifically, in attend–audition blocks PL was manipulated by playing a second sound concurrently with the AV object. Participants were asked to decipher the presence/absence of frequency modulation (phenomenologically, a warble) in the concurrent sound, and would only make the verification judgment when a warble was detected ('go') and would press a third response button and forgo the verification task when no warble was detected ('no–go'). The concurrent sound was a complex tone composed of three frequencies (200, 400 and 800 Hz). In the LL, the deviation frequency used to create the warble was 50 Hz and for the high load it was five Hz, making the discrimination between go and no–go trials more perceptually difficult in the high load condition. In attend–vision blocks a second image was shown concurrently with the AV object. Participants were asked to decipher if the concurrent image was a circle or an ellipse, and would only make the verification judgment when an ellipse was seen ('go') and would press a third response button to forgo the verification task on detection of a circle ('no–go'). The diameter of the circle subtended a visual angle of 3.6 degrees in both the low and high load conditions. In the low load condition, the diameter of the long length of the ellipse subtended a visual angle of six degrees and in the high load condition it subtended a visual angle of four degrees, again making the discrimination between go and no–go trials more perceptually difficult in the high load condition (see Figure 1 for an example of the stimuli). In each block there were 45 'no–go' trials. The 'no–go' trials were selected at random for each participant from the full corpus of 180 trials available in each block. Thus, in total there were 225 trials per block with the 'no–go' trials comprising 20%.

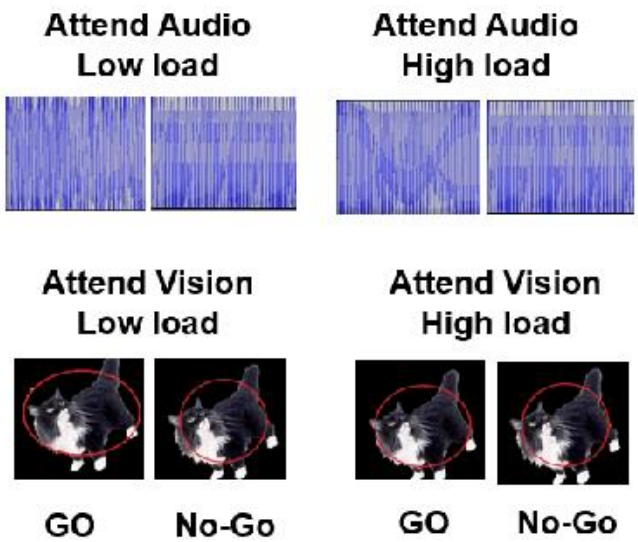

Figure 1. Examples of the stimuli used in low load and high load trials for attend–audition and attend–vision.

Procedure

Following informed consent, participants were seated in a quiet and darkened room. They first completed the standard ANT (Fan et al., 2002). In this task participants were asked to focus on a centrally presented arrow, while ignoring flanking arrows (two flanker arrows on either side). Flankers could point in the same (congruent trials) or opposite (incongruent trials) direction as the central arrow, or otherwise flankers were straight lines with no direction (neutral trials). Participants completed one block of the ANT which comprised 288 trials with 96 trials for each congruency condition. (ANT; see Fan et al., 2002, for detailed description of methods). Once this was completed participants began the main experiment. Prior to attend–vision blocks, participants were given a tutorial on the difference between the circle and ellipse images, and prior to the attend–audition blocks they were given a tutorial on the difference between the warble and the flat sounds. Each participant completed 24 practice trials for each block type. For each block each trial began with a centrally presented fixation cross for 200 ms, followed by a blank screen for 50 ms. This was followed by an audio–visual object presented for 500 ms, along with an additional visual stimulus (circle or ellipse) for the attend–vision conditions or an additional auditory stimulus (no warble or warble) for the attend–audition conditions. A printed response cue then remained on screen until a response was made. In the case of ‘go’ trials (triggered by an ellipse or warble), participants were asked to indicate if the response cue represented the object they had seen/heard by pressing one of two buttons representing ‘yes’ or ‘no’ on a response pad. In the case of ‘no–go trials’ (triggered by a circle or no warble), participants were asked to press a third (middle) button on the response box. Once a response was recorded, a 50 ms response checking period was followed by visual feedback in the form of a centrally presented green cross (correct trials) or a red cross (incorrect trials) for 500 ms. The response–stimulus interval was 800 ms (see Figure 2 for a schematic of the trial structure). Participants were asked to respond as quickly and as accurately as possible by pressing one of three buttons on a PsyScope Button Box.   The entire experiment was completed in approximately 1.5 hours.

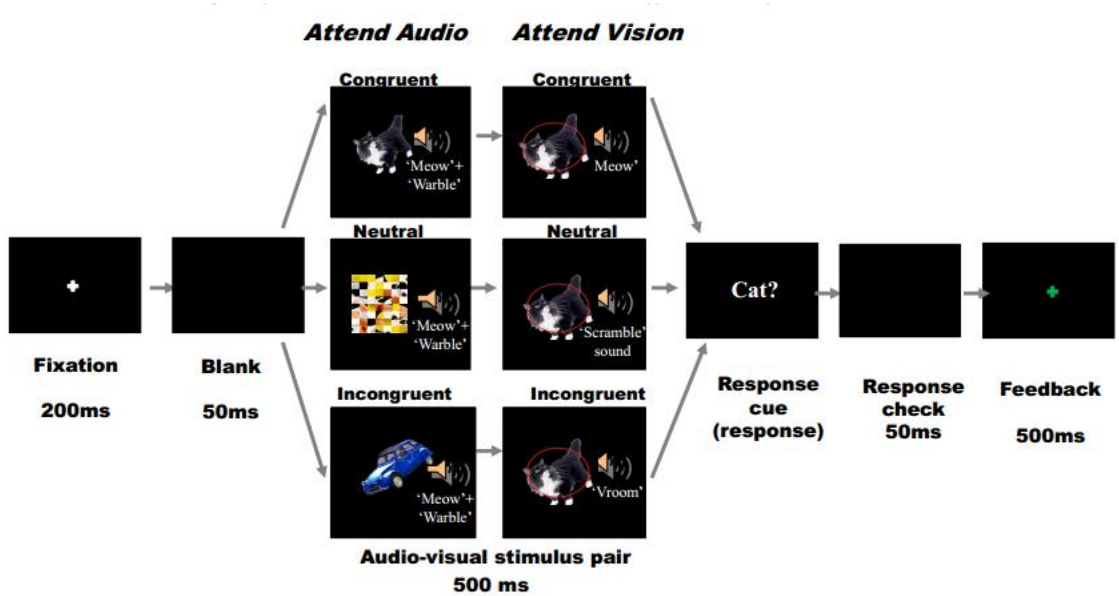

Figure 2. Schematic of the trial structure for attend–audition and attend–vision conditions.

Results

Data from 48 participants were included in all analyses unless otherwise specified. All analyses were carried out on median RT and percent error rate data. Only 'go' trials in which participants made a verification judgment were included in analysis. 'Go' trials for which participants made a 'no–go' response (e.g., responded but failed to perform the verification task) were not included in error rate analysis, as the source of such errors are not due to distractor compatibility effects, but due to an incorrect discrimination of the concurrent sound/image.

Impact of PL on cross–modal distractor processing

PL manipulation check

To ensure that the PL manipulation was successful, a 2 (attended modality; audition, vision) x 2 (load; low, high) repeated measures ANOVA was conducted on RTs and error rates, collapsed across all trial types (congruent, incongruent and neutral). RT data revealed a main effect of modality F (1,47) = 135.9, MSE = 5790000, p < .001, indicative of slower RTs to auditory (1200 ms) compared with visual (853 ms) responding. Importantly, a main effect of load F (1,47) = 25.5, MSE = 788000, p < .001 indicated slower RTs to high (1091 ms) compared to low load (962 ms) conditions (see Figure 3). The lack of interaction between modality and load (p = .783) suggests that the effect of the load manipulation was equivalent in both the auditory and visual modalities. Error rate data also showed a main effect of modality, F (1,47) = 11.68, MSE = 251.7 , p < .001, in which more efficient processing was associated with visual (5.2%) compared with auditory (7.4%) trials. A main effect of load, F (1,47) = 6.35, MSE = 59.2 , p = .015, showed lower errors on low (5.7%) compared to high (6.9%) load trials (see Figure 2). Error rate data also failed to show an interaction between modality and PL (p = .619). Both RT and error rate data suggest that the PL manipulation was successful in that participants found the high load trials more demanding than the low load trials.

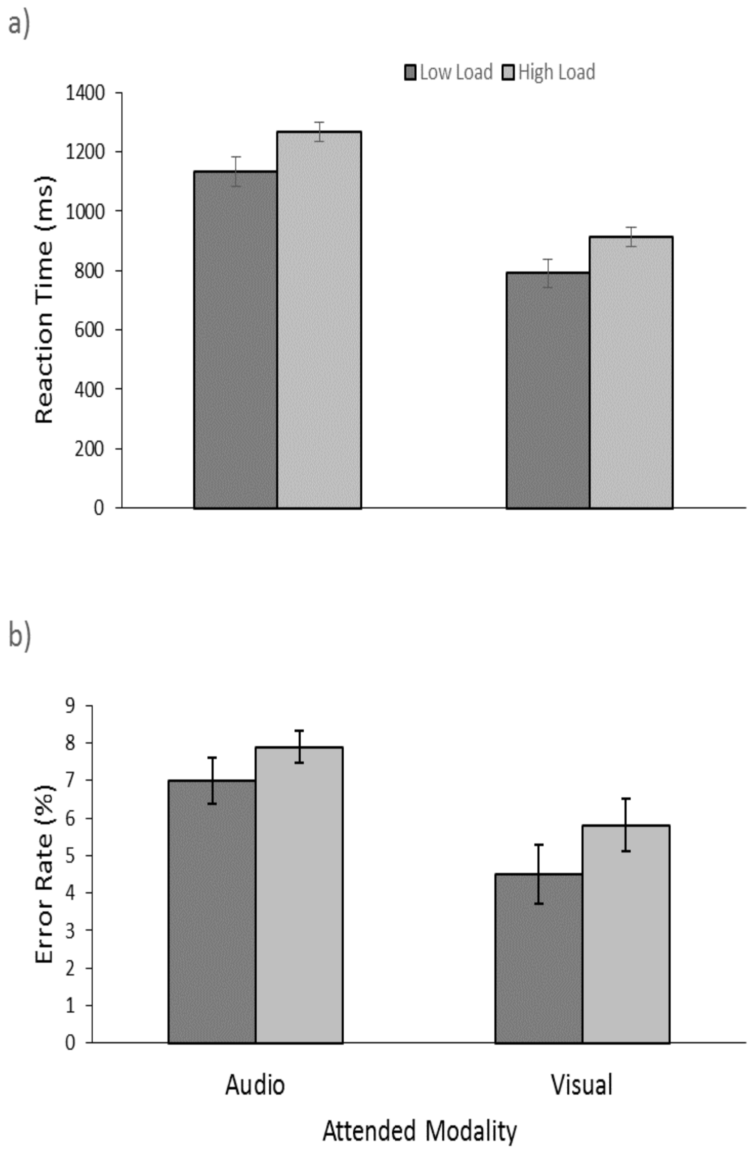

Figure 3. Perceptual Load manipulation check. Overall performance collapased across congruency in RT (Figure 3a) and error rates (Figure 3b) are shown for low load and high loadconditions for attend–audio (AA) and attend–vision (AV) modalities. Error bars represent standard error.

Distractor effects

One of the main goals of the current experiment was to assess the impact of PL on distractor compatibility effects. Distractor (incongruent – congruent) scores were entered in a 2 (attended modality: audition, vision) x 2 (load; low high) repeated measures ANOVA for both RT and error rate data. Despite the fact that distraction was clearly in evidence due to non–zero distractor scores (see Figure 4a) the data showed no significant effects (all *p*s > .066). There was a trend for a main effect of modality (p = .066), in which distractor effects were larger for auditory (139ms) compared to visual (94ms) trials (see Figure 4a). Similarly, the error rate data revealed only a main effect of modality, F (1, 47) = 15.01, *MSE* = 1223, p < .001, with more errors on auditory (9.2%) compared to visual (4.2%) responding (see Figure 4b). All other effects in error rate were non–significant (all *ps* >.098).

Overall, the data do not show any significant modulation of PL effects on cross–modal distractor processing, although numerically the data suggest a slight increase in distractor score during high relative to low load in both attend–vision and attend–audition conditions. One possibility for the lack of distractor effects in the current study is that the effect of load manifests only in terms of either facilitation or interference, or in terms of both facilitation and interference that subsequently cancel each other out. Since previous research has found differential cross–modal facilitation and interference effects (e.g. Chen & Spence, 2010; Laurienti et al., 2004) using audio–visual stimuli, and, given the currently ambiguous status of cross–modal PL effect, we felt it prudent to further examine distractor effects by looking at facilitation and interference independently. We found no significant effects of facilitation (congruent – neutral trials) in either the RT (*ps* > .59) or error (*ps* > .26) data, and do not discuss these any further (see Figures 4d).

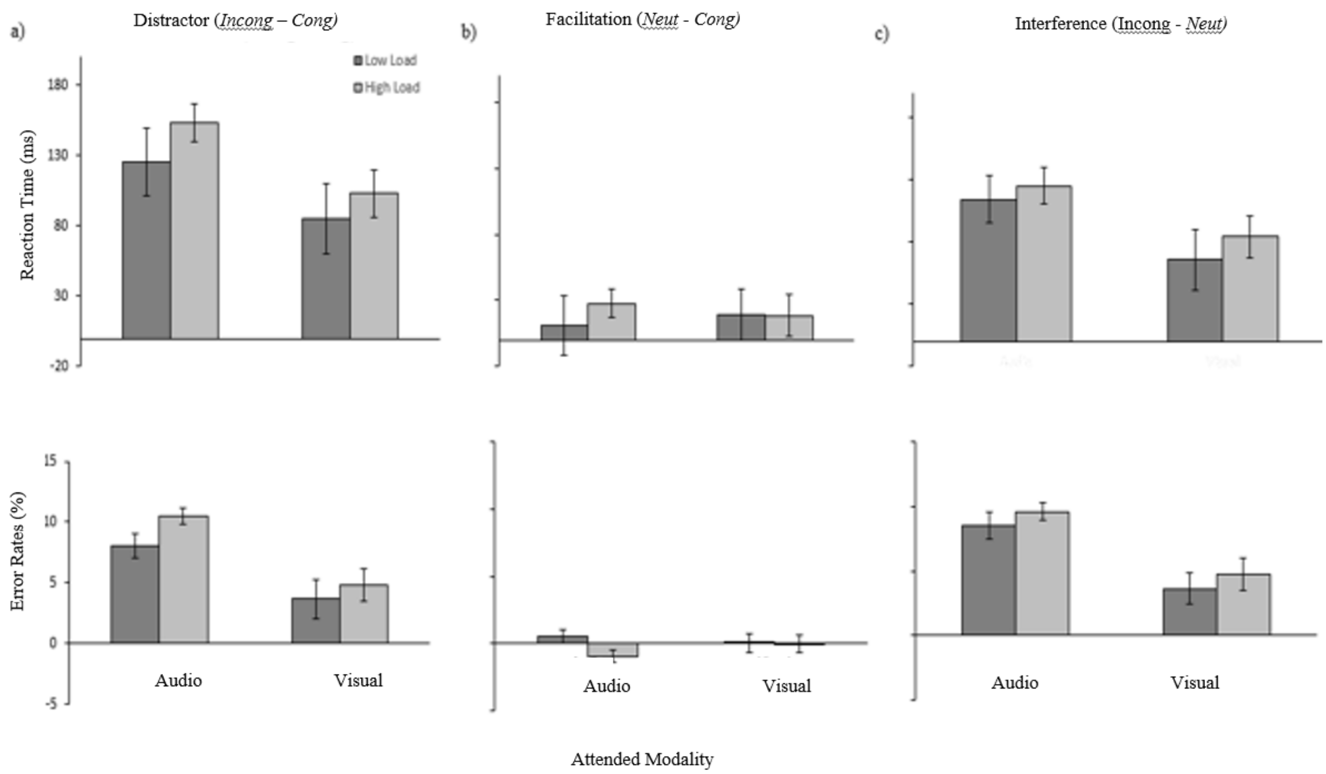

Figure 4. RT and error rates for distractor scores (a), facilitation scores (b) and interference scores (c) by modality. Error bars represent Standard Error.

Interference

Interference scores (incongruent – neutral trials) for both RT and error rate data were entered into a 2 (attended modality: audition, vision) x 2 (load; low high) repeated measures ANOVA. The RT data revealed only a main effect of modality F (1,47) = 5.863, MSE = 957, p = .019 (all others ps > .458), in which there was greater interference for auditory (120 ms) than for visual (75 ms) trials (see Figure 4c). Error rate data also revealed a main effect of modality F (1, 47) = 16.98, MSE = 1141, p < .001 (all other ps > .268) in which errors were higher on auditory (9.1%) than on visual (4.2%) trials (see Figure 4f). Although RT and error rate data showed that visual distractors interfered more with auditory target processing than the reverse, the critical effect of PL was absent suggesting that distractor compatibility effects were not dependent on the

PL of the task. Once again, numerically the data suggest a slight increase in interference score during high relative to low load in both attend–vision and attend–audition conditions.

Comparison of cross–modal and uni–modal selective attention performance

As discussed in the introduction, if perceptual resources are limited at a supramodal level, then we would expect participants to perform similarly on within and across modality selective attention tasks. On the other hand, if resources are limited at a modality level, we would not expect to find such a similarity. In order to examine these competing hypotheses, we obtained the executive function score from the ANT (incongruent – congruent trials), which is analogous to the distractor score computed in the main study. ANT RT and error rate data were independently entered into repeated samples t–tests with the factor of congruency (congruent, incongruent). Two participants were excluded on the basis of their ANT data due to error rates greater than 90% on the incongruent trials. Results from the remaining 46 participants revealed a significant difference for both the RT (t (45) = –16.29, p < .001) and error rate data (t (45) = –5.26, p < .001), with faster responses for congruent (552ms) than incongruent (650 ms) trials, and lower error rates for congruent (0.92%) than incongruent (3.75%) trials. RT and error rate distractor scores from the ANT and the main task were then correlated for each modality by load condition (i.e., AL, AH, VL, VH) for each participant using Pearson's r and Bonferonni corrections were applied for multiple comparisons. While the RT data revealed no significant correlations (AL = .12; AH = –.07; VL = –.02; VH = .00; all ps > .418), error rate scores were significantly correlated between the ANT and both AL (r = .37, p >.05) and AH (r = .48, p > .05) conditions (VL = –.05; VH = –.02; ps > .746). These results reveal that while participants completed the attend–audition conditions, the degree to which visual distractor processing influenced responding was positively correlated with the degree of visual distractor processing evidenced in the (uni–modal, visual) ANT task. While numerically the correlation is higher in the AH condition, the data suggest that the correlation in the AH condition may have been inflated due to a few participants who showed fairly high error rates on the main task. However, since exclusion criterion was based on average errors across all conditions in the main task, these participants did not meet exclusion criterion and thus were retained in the analysis. Despite any putative difference in the strength of the correlation between AL and AH condition, visual distractor processing was correlated across tasks and there was no such correlation between visual ANT and auditory distractor processing as measured in the attend–vision conditions.

The impact of processing efficiency

While there was no significant effect of PL during either visual or auditory responding, there were significant (error rate) and trending (RT) effects of modality for distractor scores, with auditory targets being more influenced by visual distractors than visual targets being influenced by auditory distractors. One possibility is that this effect is not reflective of some intrinsic property of visual and auditory modalities, but simply reflects processing efficiency wherein the faster modality has a larger impact on the slower modality (Mordkoff & Yantis, 1991). To investigate this, a processing efficiency measure was obtained by averaging auditory performance for neutral trials across low and high loads, averaging visual performance for neutral trials across low and high loads, and subtracting the visual score from the auditory score. This measure was then correlated with distractor scores for each modality and load condition, to determine if those individuals showing greater processing efficiency for vision would also show greater effects of visual distractors.

The results revealed no significant correlations in the RT data (all *p*s > .181). Error rate data showed a significant positive correlations between processing efficiency and distractor scores

(.54) scores in the AHL condition (all other *p*s > .101). This positive correlation suggests that greater differences in processing efficiency favouring vision were correlated with greater effects of visual distractor during the attend–audition (high load) condition. While these results provide support for a processing efficiency account of the observed modality asymmetry between auditory and visual attention, they cannot provide a full account, as this effect was seen in only the AH load condition even though the modality asymmetry was seen across all load conditions.

Discussion

The current study sought to investigate the impact of PL on cross–modal distractor processing. Methodological adjustments were made from previous studies in that our PL manipulation did not contain a set size change (e.g., Tellinghuisen & Nowak, 2003) and so avoided the potential confound of dilution (e.g., Benoni & Tsal, 2010). Moreover, we did not include stimuli thought to be immune to manipulations of PL (i.e., faces; Vroomen et al., 2001). In addition, we used spatial, temporal and semantic correspondence between our auditory and visual stimuli to promote distractor compatibility effects. Finally, audition and vision served as both the targets and the distractors, so we could determine if the effect of PL were dependent on the target modality, as has been suggested by previous researchers (Jacoby et al., 2012). Our data confirm the successful manipulation of load in terms of both RT and error rate disadvantages associated with high load (see Figure 3), and that attend–vision (with auditory distractor) conditions generated faster and less errorful responding than attend–audition (with visual distractor) conditions. The primary finding in the current study was that while distractor processing was clearly in evidence, it was not impacted by the PL of the task. This seemed to be irrespective of whether the targets were auditory (and the distractors visual) or the targets were visual (and the distractors auditory). A further analysis of distractor effects into its component parts revealed a negligible contribution for facilitation on congruent trials but a sizable contribution for interference on incongruent trials, consistent with previous investigations of cross–modal selective attention (e.g., Yuval–Greenberg & Deouell, 2009). In neither case though did PL significantly modulate the degree of these effects. This initial finding suggests that PL does not have the same impact on cross–modal distractors as it does on within–modality distractors. This difference between uni–modal and cross–modal distractor processing was also supported by our distractor effect correlations between the main task and the ANT task. The only correlations to reach significance were between the ANT and the attend–audio low and high load conditions suggesting that while the ability to ignore visual distractors within and across modalities was correlated among participants, there was no such correlation between the ability to ignore auditory distractors and visual distractors. Third, we found partial support for a processing efficiency account in the observation of a significant positive correlation between processing efficiency and distractor effects during AH conditions. These data are in accordance with uni–modal horse–race models of processing (Mordkoff & Yantis, 1991) where the differential speeds of processing for two types of information influences in degree of interference one has on another. The implications of these findings on the application of PLT to cross–modal distractor compatibility effects, and level at which capacity limitations may arise, will now be discussed in turn.

Three measures of distractor compatibility were assessed in the current study. First a distractor score was obtained by subtracting performance on congruent trials from those of incongruent trials. While distractor scores are typically used to assess PL effects, such scores do not offer any insights as to whether the distractors have more of a facilitative or an interfering effect. Given that previous studies have often found stronger effects of interference than facilitation on target processing (e.g., Yuval–Greenberg & Deouell, 2009), we also computed facilitation (neutral – congruent trials) and interference (incongruent –neutral trials) scores. We did not find evidence for modulation on any of these selective attention measures by PL in either the RT or the error rate data. While the lack of distractor processing modulation by PL found in the current study is in contrast to visual uni–modal selective attention findings, our results are aligned with a growing body of cross–modal PL studies which find that PL does not have the same impact on cross–modal distractors as it does on within–modality distractors (Vroomen, et al., 2002, Tellinghuisen & Nowak, 2003, Jacoby et al., 2013). Statistically, our results align with Vroomen and colleagues (2002) who also did not find modulating effects of PL on the compatibility effects of distracting faces on emotional voice perception (attend–audition, visual distractor condition). As already noted, these researchers used face and voice stimuli which due to their highly salient nature may be unaffected by PL even in the visual domain (Lavie et al., 2003). Although their findings may be more related to their choice of stimuli than to the impact of PL on cross–modal distractor compatibility effects, we rule out the possibility that the choice of stimuli is the sole determinate of a PL null effect as we used less emotionally laden stimuli (everyday objects and animals) and showed the same relationship. It could additionally be argued that the use of more naturalistic stimuli than is typical for PL investigations might be the driving force in showing immunity to PL effects. This is unlikely to be the case as Lavie, Lin, Zokaie and Thoma, (2009) used similar naturalistic stimuli in the uni–modal visual domain and obtained evidence for the modulation of distractor processing by PL.

Related to the naturalist nature of the stimuli used in the current study, recent work by Rapp and Hendel (2003) suggests that when the target and distractor are processed at different levels (e.g., the distractor undergoes a more perceptual analysis while the target undergoes a more semantic analysis), PL does not modulate distractor processing. While in the current study targets and distractors were both naturalistic stimuli, PL was modulated at a lower level (e.g., visual discrimination between a circle and ellipse) and thus it may be argued that our PL manipulation failed to exhaust processing resources related to the higher level object naming task, thus explaining why distractor processing was not modulated by PL. However, we do not think this is the case as Lavie and colleagues (2009) used a similar design in the uni–modal visual domain in which PL was modulated at a low–level (set size) while the main task was an object naming task, and in this study, PL successfully modulated distractor processing. Another point related to the use of naturalistic stimuli is that interactions among audio and visual inputs are typically stronger when there is asynchrony between the two modalities such that the audio component of the stimulus is presented at a slight lag with respect to the visual component of the stimulus (Chen & Spence, 2010). This suggests that the distractor effects in the current study, although present, may be weaker overall compared to a design that included an audio lag, and thus the lack of distractor modulation may be due to overall lower distractor effects. This is also unlikely to be the case given that previous research has shown that regardless of the overall level of distractor effects, the pattern of modulation of these effects remains consistent (Beck & Lavie, 2005). Specifically, these authors found that although presenting distractors in a central location compared to a peripheral location increased overall distractor effects, the pattern of distractor modulation based on PL was consistent for both types of distractors. Furthermore, this finding suggests that given that we used central distractor presentation, this would already have increased the impact of our distractors relative to the more typically used peripheral distractors.

In the current study, although there were no significant modulations of distractor effects by changes in PL, numerically our data are aligned with Tellinghuisen and Nowak (2003), who found that increased auditory PL actually led to increased visual distractor processing, the opposite to what is predicted by PL theory. Figure 3 shows that for our distractor and interference scores participants had numerically greater distractor compatibility effects in the high compared to the low load conditions. One possibility is that the current study would have found modulation of distractor compatibility effects by PL with sufficient power. This is unlikely given that we had the same number of conditions as Tellinghuisen and Nowak (2003), but we had more participants (48 in the current study compared with 30) as well as more observations per cell (60 in the current study compared with 24). Irrespective of the way in which the data are considered, both interpretations have a precedent and neither is consistent with a standard PL account taken from the visual literature: as PL increases the influence of distractors should decrease (Lavie 1995), rather than stay the same (current statistical outcome; Vroomen et al., 2001) or increase (current numerical trend; Tellinghuisen & Nowak, 2003).

The lack of modulation of distractor compatibility effects by PL in the current study supports the view that capacity limits arise at the modality level (Treisman & Davies, 1973; Wickens, 1980, 1984; Duncan et al., 1997). Further support for modality limited capacity is provided from the correlational analysis between participants' performance on the current task and the standard visual ANT (Fan et al., 2002). The current results showed correlations between participants' distractor scores on the ANT and the attend–audition (visual distractor) conditions of the current task. This is important given that the ANT (based on RT and error rate data) can be considered a low load task, in which much of the visual processing resources are spared and so can be directed towards distractors. Given that this putatively low load visual task correlated with both AL and AH load in the main task, then regardless of the successful manipulation of auditory load the extent of visual distractor processing was not modulated, suggesting that increasing auditory load does not deplete visual resources. Moreover, in a study by Forster and

Lavie (2007) the authors show that while inter–individual differences in selective attention abilities impacted distractor processing at low load, they failed to do so at high load, since this condition putatively exhausted processing resources for all participants. In the current study, our load manipulation was successful, and thus the finding that inter–individual differences in ignoring visual distractors were correlated in our task and the ANT during both AL and AH load also supports differences in the impact of cross– and within–modality distractor processing. Finally, the failure to find a correlation between attend–vision conditions, in which the distracting information is auditory, and the visual ANT, further suggests that participants' abilities to ignore auditory and visual distractors are independent. This independence is also supported within the main task, as a main effect of modality was found for both distractor and interference scores in the error rate data, again suggesting a difference in participants' ability to ignore auditory and visual distractors.

One potential explanation for the modality asymmetry in distractor compatibility effects is processing efficiency. Based on horse–race models, it would be expected that the more efficiently processed modality would interfere more with the less efficiently processed modality. In order to examine this possibility we computed processing efficiency scores by averaging participants' performance on neutral trials in attend–audition conditions and in attend–vision conditions. The results revealed a significant correlation between processing efficiency and distractor compatibility effects during AH load. Specifically, the more errorful participants were on auditory compared to visual processing, the more they were impacted by visual distractors. This result confirms a role for processing efficiency in the asymmetry between distractor compatibility effects in attend–audio conditions and further confirms that horse–race models based on uni–modal processing can be successfully applied to cross–modal processing (Sandhu

& Dyson, 2012, 2013; Benjamins, van der Smagt & Verstraten, 2008). However, given that this effect is only seen in the auditory high load condition suggests that other factors must also be at play. In the current experiment, a modality asymmetry, indexed by a main effect of modality, was significant for interference scores in error rate and RT data, and was significant for distractor scores in error rates while trending for RT data (p = .066). Thus, if processing efficiency was the main contributing factor driving the asymmetry we would expect to see significant correlations in all conditions, and not just AH load. It should also be noted that this correlation was also strengthened by two participants who both showed relatively high error rates on the ANT task.

Given that processing efficiency cannot provide a full account of the modality asymmetry present in the current study, other possibilities warrant consideration. The modality appropriateness hypothesis (Welch & Warren, 1980) suggests that processing of specific types of information has a preferred modality. For example, vision tends to dominate in spatial processing (e.g., Bermant & Welch 1976; Bertelson, 1999; Bertelson & Aschersleben, 2003; Morein–Zamir, Soto–Faraco, & Kingstone, 2003; Recanzone, 2003) while audition dominates in temporal processing (e.g., Kubovy, 1988). Early work suggested that vison is also the dominant modality for object processing (Rock & Victor, 1964; Hay, Pick & Ikeda, 1965) and this view is still favoured by more recent work (Sinnett, Spence & Soto–Faraco, 2007; Yuval–Greenberg & Douelle, 2009; although see Robinson & Sloutsky, 2004 for a discussion of auditory dominance in early development). The current results also support visual dominance in object perception as vision had greater processing efficiency for objects than audition under both intact and degraded conditions. However, the specific parameters of our task may also play a role in promoting visual over auditory dominance. While both attend–vision and attend–audition conditions had the target object and the go–no–go object presented in the attended modality, it is very difficult to compare the impact of the circle/ellipse versus the flat/warble tone on target object processing in vision and audition, respectively. For example, it may be the case that the auditory flat/warble sound masked more of the auditory target object than did the circle/ellipse in the attend–vision condition. Furthermore, our design may have favoured vision as the response cue and feedback were provided in the visual modality. Indeed previous work in which all cues and feedback were presented bi–modally revealed patterns of auditory rather than visual dominance (Sandhu & Dyson, 2012). Future research that includes a baseline so as to obtain a measure of processing efficiency, and also presents all cue and feedback information in both modalities would be in a good position to provide a stronger test of modality dominance in object perception.

Overall, the main aim of the current study was to assess the impact of PL on cross–modal distractor compatibility effects. We were able to show three important effects, namely, a) that there was a significant main effect of PL, b) that the visual distractor effects we observed in the current design positively correlated with standard visual distractor effects in the ANT, and, c) different speeds of processing between the two modalities partially predicted the degree of interference in accordance with uni–modal horse–race accounts of processing. Despite all of these standard effects, we found that PL failed to modulate distractor compatibility effects. Future research should examine the correlations between uni–modal (i.e., auditory versions of the ANT; Roberts, Summerfield & Hall, 2007) and cross–modal PL manipulations on auditory distractor processing, to determine if the ability to ignore auditory distractors would be correlated across low load uni–modal and both low and high load cross–modal conditions, as was the case for visual distractors in the current study (see Francis, 2010, and, Gomes et al., 2008, for varying opinions on the nature of PL in audition). This systematic comparison would help further resolve the current discrepancies between uni–modal and cross–modal literatures. Overall, the results of the current study highlight differences in auditory and visual selective attention abilities, and suggest that attentional capacity limitations arise at the modality level.

Chapter 3: Experiment 2. The impact of SD on cross–modal distractor processing

Abstract

During the recognition of natural objects, visual information tends to dominate over auditory information however, this dominance is not fixed and can be impacted by factors such as SD. Examining the impact of SD on audio–visual selective attention, we aimed to a) replicate findings of reduced visual dominance by visual degradation, and examine the impact of auditory degradation on modality dominance, b) decompose distraction effects into its facilitation and interference constituent parts, c) explore whether any observed visual dominance could be accounted for by processing efficiency, and, d) correlate performance on our cross–modal task with a standard uni–modal attentional network task (ANT) to determine the extent to which selective attention abilities are stable across uni–modal and cross–modal domains. We replicated findings of decreased visual dominance in degraded relative to intact attend–vision conditions, and extended these to increased visual dominance in degraded relative to intact attend–audition conditions. While degradation increased distractor processing for both audition and vision, the increase manifested in terms of interference for vision, and facilitation in audition. Facilitation effects were in line with a processing efficiency account, where the less efficient modality received more distraction from the more efficient modality. Finally, we found no correlations between our cross–modal task and the ANT task suggesting the lack of shared mechanisms between uni– and cross–modal attentional processes. The results are discussed in terms of modality dominance, and the impact that focusing on sight or sound has on determining the interplay between the senses.

Introduction

In daily life we are often presented with information from multiple sources and this problem is compounded by stimulus delivery across multiple sensory modalities. Therefore, it is important to be able to attend to information coming from one modality while ignoring information presented in a second modality. One factor that is thought to impact such cross–modal attention is the type of information presented by each modality (modality appropriateness hypothesis; Welch & Warren, 1980). For example, in the classic ventriloquist effect, the location of an auditory stimulus is influenced by that of a visual stimulus (Radeau & Bertelson, 1987) such that when presented with audio–visual stimuli from spatially distinct locations, the perceived location of the sound is drawn towards the location of the visual object. This is thought to be due to the fact that localization abilities in humans are stronger in the visual compared to the auditory modality (e.g., Bermant & Welch, 1976; Bertelson, 1999; Bertelson & Aschersleben, 2003; Morein–Zamir, Soto–Faraco, & Kingstone, 2003; Recanzone, 2003). While vision tends to dominate in spatial processing, audition dominates in other domains such as speech perception such that individuals presented with audio–visual speech (voice and talker face) information tend to weigh the auditory information more strongly (e.g., Alsius, Navarra, Cambell, & Soto–Faraco, 2005). Thus, research demonstrates that the each sensory modality has its strengths in terms of the type of information transmitted, and perceptual decisions tend to be based on the more accurate modality.

Despite these canonical ideas in which vision is the preferred modality for spatial processing and audition is the preferred modality for speech perception, we also appear delicately tuned to the *on–going* quality of modality information. In a key paper, Ernst and Banks (2002) demonstrated that under conditions of divided attention participants weighted sensory information on a trial–by–trial basis, such that the modality with the more reliable signal influenced perception to a greater degree than the modality with the less reliable signal. This paper was instrumental in demonstrating the dynamic nature of attentional processes as well as the role of signal reliability in the allocation of cross–modal attention. While the original work by Ernst and Banks (2002) examined the impact of visual signal reliability on the processing of haptic stimuli, subsequent research in the audio–visual domain has demonstrated similar effects of visual signal reliability on auditory processing (e.g., Alais & Burr, 2004; Hairston, Laurienti, Mishra, Durdette & Wallace, 2003). Importantly, research has demonstrated that the typical weighting of vision that occurs for spatial processing can be modified by manipulating the signal reliability of the visual input (e.g., Alais & Burr, 2004; Hariston, Laurienti, Mishra, Durdette & Wallace, 2003; Rohe & Noppeny, 2015). For example, Alais and Burr (2004) failed to find typical ventriloquist effects when the visual signal was made unreliable via extreme blurring. Similarly Hariston et al., (2003) found that the addition of an auditory stimulus under conditions of audio–visual presentation significantly improved localization ability over a visual only stimulus, but only when vision was degraded by induced myopia. Similarly researchers have shown that the typical favouring of audition during speech processing can be manipulated via auditory signal reliability. Specifically, visual speech cues have stronger impacts on speech perception when the auditory signal is unreliable compared to when it is reliable (e.g., Sekiyama, Kanno, Miura & Sugiat, 2003; Ma, Zhou, Ross, Foxe & Parra, 2009; Nath & Beauchamp, 2011). These findings suggest that when asked to attend to multiple modalities, the more informative modality, based on the nature of the information *and* the signal reliability of each modality, is weighted more strongly.

While we often are required to attend to multiple modalities at the same time, there are also situations in which we need to focus on one modality while ignoring information presented in another. For instance, if you are reading, you may need to block out the voice of someone having a conversation nearby. The ability to attend to information presented in one modality while ignoring information presented in another modality is referred to as cross–modal selective attention (for a review see Driver, 2001). Given that signal reliability impacts cross–modal attention when attending to multiple modalities, it stands to reason that it would also impact the success of cross–modal selective attention. In line with this reasoning, recent studies directly assessing the impact of signal reliability on selective attention have shown that distracting information has a stronger influence on perceptual processing when the target information is degraded and thus has lower signal reliability (e.g., Yuval–Greenberg & Deouell, 2009; Noppeney, Ostwald, & Werner, 2010; Collignon, Girard, Gosselin, Roy, Saint–Amour, Lassonde, & Lepore, 2008). For example, Yuval–Greenberg and Deouell (2009) presented participants with audio–visual stimuli that represented realistic objects with the assumption that vision would be the dominant modality for object recognition. These authors were interested in how this dominance would be impacted by signal reliability of the visual input. A single trial consisted of a natural sound paired with an image representing a natural object such that both the image and sound could represent the same object (congruent trials), different objects (incongruent trials), or the attended modality represented a natural object while the unattended modality represented a neutral image/sound that did not correspond to any particular object (neutral trials). In order to assess the impact of signal reliability on distractor processing, the image could be presented either intact (full contrast) or degraded (low contrast). Participants were asked to verify if the word presented following the audio–visual stimulus represented the object they perceived in the attended modality. For example, under attend–audition conditions, if presented with the sound of a dog ('woof') and the image of a cat, and were asked to verify the word 'DOG', they would respond with 'yes'. The authors found that under intact visual presentation, visual distractors interfered more during auditory responding than auditory distractors on visual responding. However, this visual dominance effect decreased by degrading the visual signal reliability. Specifically, when the contrast of the visual image was reduced so that it was harder to parse from the background, the impact of auditory distractors on visual processing increased relative to when the visual image were presented in full contrast. This suggests that the degradation of the visual stimulus led to a reweighting of signals, such that auditory distractors had a greater impact on trials in which vision was degraded compared to intact. Similar effects were also found by Noppeney et al. (2010) using a comparable audio–visual object recognition paradigm. Here the researchers found that although auditory distractors impacted on visual processing both when the visual signal was intact and when it was degraded (via white noise), the amount of interference generated by the auditory information was significantly increased when the visual stimuli were degraded.

While these studies both show the effects of auditory distractors on cross–modal visual selective attention, there is evidence that a similar pattern of results (greater interference from distractors when target information is degraded) is also observed when audition serves as the target modality and vision as the distractor. Collignon et al. (2008) presented participants with emotional speech information in both the visual (face) and auditory (voice) domain and asked participants to characterize the emotion based solely on the auditory or the visual modality. They found that when participants were asked to attend to audition, distraction by vision was greater when the auditory signal was degraded than when it was intact. The research reviewed above demonstrates a reliable effect of increased distraction under conditions of selective–attention when targets are degraded compared to when they are intact. This effect suggests that similar to conditions of divided attention, under conditions of selective attention, the more reliable signal leads to greater distraction. However, this cannot provide a full explanation of increased distraction under degraded conditions, as it does not explain why selective attention fails in the first place. One explanation for the failure of selective attention in degraded conditions can be gleaned from a basic tenant of multimodal integration, which is the principle of inverse effectiveness (Meredith & Stein, 1983). This principle states that cross–modal integration is most likely to occur when the incoming sensory information is weak. Under conditions of selective attention, this can be thought of as a widening of attentional scope to include the unattended modality, as integration cannot occur while simultaneously inhibiting the distractor modality. This notion is supported by evidence to suggest that integrating information from multiple sensory modalities makes selective attention harder, and leads to increased distraction (e.g., Driver & Spence, 2004; Spence, Ranson & Driver, 2000). Thus, taken together, the principle of inverse effectiveness, and the findings of Ernst and Banks (2002), suggests that when the target information is degraded, there is a widening of attentional focus to the unattended modality, and that this modality will be given more weight due to its relative reliability over a degraded target.

The studies reviewed show that the extent of distraction provided by a modality is in part dependent on the signal reliability of the target information, such that greater distraction is seen when the target is degraded. A more nuanced question can also be asked regarding the nature of distraction, and whether the effect is driven by interference during incongruent trials and / or facilitation during congruent trials. The question can be answered by the addition of a neutral trial, where a sound is paired with a neutral image or an image paired with a neutral sound (e.g., Yuval–Greenberg and Douelle, 2009). Facilitation then is defined as faster responding on congruent relative to neutral trials and interference is defined as slower responding on incongruent relative to neutral trials. Yuval–Greenberg and Douelle (2009) found that the impact of auditory distractors on visual targets manifested exclusively as interference effects, with no significant differences in the amount of facilitation during intact or degraded conditions. In contrast Colligon et al. (2008) found evidence for both interference and facilitation effects in the context of audio–visual emotion integration. These contrasting effects may be due to the use of a uni–modal baseline in Colligon et al. (2008) during which either auditory or visual information was presented and a multi–modal baseline in Yuval–Greenberg et al. (2009). Recent research shows that there is a multisensory facilitation benefit that speeds up processing for bimodal compared to unimodal stimuli that is distinct from cross–modal congruency effects requiring participants to assess the relatedness of the audio and visual components of the stimuli (Diaconescu, Alain & McIntosh, 2011). Specifically, these authors found that the effects of multisensory facilitation occurred earlier in time and at distinct neural locations than cross–modal congruency effects (see also Sinnett, Soto–Faraco and Spence, 2008). Thus, in order to determine if distractor effects are due to facilitation or interference, it seems that a neutral bimodal baseline condition should be favoured. Unfortunately, although Yuval–Greenberg and Doeuelle (2009) do include such a baseline condition, they were only interested in the effects of visual signal reliability on auditory distractor processing, so it remains unclear if degrading auditory target information would also led to interference effects in the absence of facilitation effects. Comparing unimodal to bimodal trials, Sinnett et al., (2008) found that bimodal auditory trials were slowed down relative to unimodal auditory trials, while bimodal visual trials were sped up relative to unimodal visual trials. While this study was looking at the benefits of multisensory over unisensory processing, rather than cross–modal conflict, the results do suggest that different patterns of facilitation and interference can emerge depending on the target modality.

The importance of an orthogonal design in which both audition and vision serve as the target and distractor modalities is further highlighted by the findings of Jacoby, Hall and Mattingley (2012) who found opposite effects of visual and auditory distractors on visual targets. While this study was interested in the modulating effect of perceptual load on audio–visual selective attention, this study nonetheless demonstrates that the effects of auditory and visual distractors may not always operate in the same manner.

Finally, in addition to the nature of the information, and the signal reliability of target information, another factor that can influence cross–modal selective attention is individual differences (ID) in attentional control. The notion that individuals vary in their ability for selective attention has long been recognized and has received early empirical support (e.g., Tipper & Baylis, 1987; Mihal, Barrett & Gerald, 1976). Today there exists a large body of evidence demonstrating individual differences in the ability for unimodal distractor processing across a variety of tasks including inattentional blindness (e.g., Hannon & Richards, 2010; Richards, Hannon, & Derakshan, 2010; Simons & Jensen, 2009; Seegmiller, Watson & Strayer 2011), visual Stroop task (e.g., Kane & Engle, 2003), inhibiting saccades to peripheral distractors (e.g., Unsworth, Schrock, & Engle, 2004; Kane, Beckley, Conway & Engle, 2001) dichotic listening paradigms, (e.g., Conway, Cowan & Bunting, 2001; Colflesh & Conway, 2007) and attentional blink tasks (e.g., Martens, Munneke, Smid, & Johnson, 2006; Martens &

Johnson, 2009; Martens & Valchev, 2009; Feinstein, Stein, Castillo & Paulus, 2004; Mclean & Arnell, 2011).

While this body of work suggests robust variability in individuals' ability for selective attention, very little research has assessed how such ID might interact with other factors affecting selective attention. For example, Forster and Lavie (2007) found that while there was evidence for individual variability for distraction at low perceptual load during a visual selective attention task, they found that this individual variability was reduced during high perceptual load conditions. Forster and Lavie interpret this finding in terms of processing resources, such that in the low load condition the target does not use all available processing resources, and thus individuals will vary in their control of the leftover resources and thus in the amount of distractor effects they experience. In contrast in the case of high load, most processing resources are used up by the target task, and thus there are less resources that can be controlled, reducing individual variability in the amount of distractor effects. The expected effects in the SD case are less clear. Specifically, degraded conditions are thought to represent data limited processing, which cannot be resolved by the deployment of additional resources towards the target (Norman & Bobrow, 1975). Thus following from Forster and Lavie, (2007) we may expect to see effects of ID in SD conditions, given that resources are not being used on target processing, and are being shifted towards the distractor modality, and as such, those individuals with greater attentional control may be able to limit distractor processing to a greater degree. However, given putative *intentional*[4] widening of attentional focus to include the distractor stimuli we may not expect to

[4] The term intentional here does not imply intentions in terms of top-down control by the participant, but instead that the perceptual system has a mechanism for dealing with degraded information that includes widening the attentional focus to include additional information from other sensory modalities (Meredith & Stein, 1983). Given the finding of increased distraction under uni-modal degraded conditions (Lavie & de Fockert, 2003), this attentional widening may not be limited to other modalities, but more generally to other information in the sensory environment.

find impact of ID in degraded conditions. As discussed above, in the case of cross–modal selective attention support for a widening of attentional scope during degraded conditions comes from findings of an increased likelihood of integrating the target and distractor modality, (Meredith & Stein, 1983), as well as the re–weighting of information in favour of the non–degraded modality (which in selective attention tasks is typically the distractor). As such in degraded conditions, participants may not be trying to inhibit distractor processing and thus the impact of ID in attentional control may not be observed. However, to our knowledge no study has yet tested a potential interaction of ID in attentional control and SD on selective attention and thus empirical evidence is required to assess the impact of ID on distraction under conditions of SD.

The current study had four primary aims. The first was to attempt to replicate previous findings of visual dominance in object recognition tasks (Yuval–Greenberg & Douelle, 2009), and to extend these findings to determine if signal reliability impacts distractor processing to a similar degree when the targets are auditory or visual. Second, we sought to unpack distractor effects into their constituent parts: facilitation or interference. Previous work by Yuval–Greenberg and Douelle (2009), found that degrading visual targets led to increased interference by auditory distractors, but not increased facilitation. In addition to attempting to replicate this finding, we are also interested in determining if a similar pattern will emerge for visual distractors under conditions of auditory target degradation.

Third, in the presence of visual dominance effects under intact object recognition (indexed by greater effects of visual distractors on auditory targets than vice versa), we thought it necessary to determine if the effect was due to modality appropriateness (Welch & Warren, 1980) where vision has more fidelity for object recognition, or simply due to a processing efficiency account. Specifically, using neutral trials similar to those in Yuval–Greenberg and Douelle (2009), we computed a processing efficiency score for both auditory and visual target processing. If any observed dominance was due to the faster modality having a larger impact on the slower modality, then those individuals with a greater difference in their baseline processing of audition and vision should also show greater distraction by the faster modality.

The final aim of the current study was to examine potential interactions between SD and individual differences in attentional control. To this end we had participants complete a standard ANT task which has been shown to reveal ID in attentional control (Fan, McCandliss, Sommer, Raz & Posner, 2002). We then correlated performance on this task with the main cross–modal object identification task under both intact and degraded conditions, and for both attend–audition and attend–vision conditions. If SD leads to an intentional widening of attentional focus, then we would only expect to find a correlation between the main task and the ANT task under intact conditions when there the distractors are being inhibited.

Method

Participants

Fifty–four healthy adults from Ryerson University and the surrounding community participated in the study for course credit or pay. Six participants were excluded from data analysis due to average error rates across all conditions being greater than 25%. The remaining 48 participants comprised 42 females and 41 right handed individuals. The mean age was 21 years (age range 17–48 years).

Stimuli and Design

15 images and 15 sounds were selected, representing visual and auditory components of an object belonging to one of five categories (animals, electronics, instruments, tools or

vehicles), with three possible exemplars from each category (animals; cat, cow, dog: electronics; camera, clock, phone: instruments; guitar, piano, trumpet: tools; drill, hammer, saw: vehicles; car, helicopter, plane). Auditory stimuli were taken from the Sounds and Pics stimulus set (Saygin, Dick, & Bates, 2005) and visual stimuli were taken from the Mulitmost set (Schneider, Engel & Debener, 2008). In order to attempt to equate auditory and visual responding in terms of processing efficiency, visual object stimuli were further rotated 30 degrees to the left or right (Rees, Russell, Frith & Driver, 1999; Sinnett, Spence & Soto–Faraco, 2008) leading to 30 object images and 15 object sounds. Finally, in addition to the object stimuli, a neutral visual image and a neutral sound were used. The neutral visual image was created by scrambling five additional object images from the Mulitmost set and recombining them in a random order using Photoshop software (based on Yuval–Greenberg & Deouell, 2009). The neutral sound was created by taking five additional 100 ms sound clips taken from the Sounds and Pics stimulus set and playing them sequentially for a duration of 500 ms. A five ms onset and offset ramp was included in each 100ms sound to minimize clicking effects during sound presentation. In order to attempt to minimize the impact of processing efficiency on the results, a pilot study was conducted to determine the effects that various methods of stimulus degradation would have on auditory and visual processing. The results of this study (appendix A for a full report of this study) revealed that the addition of white noise led to the most similar performance decrement in each modality. As such stimuli in the main experiment were degraded by the addition of white noise. In order to create the degraded visual condition Gaussian noise (199%) was added to the each stimulus. Similarly in order to create the degraded auditory condition Gaussian noise was also used. Different amounts of noise were required for each sound in order to equate for subjective difficulty (based on experimenter). Thus the range of added Gaussian noise across all auditory stimuli was 4% – 110%, and noise was added using MATLAB software (see Figure 5 for an example of the intact and degraded auditory and visual stimuli). Although there is large variation in the amount of noise added to subjectively equate for difficulty, given that all stimuli were presented an equal number of times in all conditions, any slight differences in difficulty for a given object should not have systematically influence the results.[5] All auditory stimuli were presented via Harman/Kardon speakers placed approximately 25 inches apart, on either side of a 15 inch Apple Studio Monitor on which visual stimuli were presented. All auditory stimuli were 500 ms and were intensity normalized with SoundEdit software. Loudness measured by a Scosche SPL 1000 sound level meter ensured that auditory stimuli were all presented at approximately 78 dB(C). All visual stimuli were fit to a five by five cm square area, and were presented centrally on a black background. Participants were seated in a quiet, darkened room approximately 57 cm from the computer monitor. All stimuli were presented using Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993) and participants' speed and accuracy in responding was recorded by Psyscope software.

Congruency was manipulated within a block by having the information in the auditory and visual modality represent the same object (congruent), represent a different object from a different category (incongruent) or represent a realistic object in the attended modality while the unattended modality was a scrambled image or sound (neutral). On congruent and neutral trials, there was only one possible pairing of auditory and visual information (i.e. dog image and dog

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[5] This experiment was initially going to be included in a larger experiment, and thus in addition to the object stimuli, for the visual stimuli a red ellipse subtending 6 degrees visual angle, placed in the center of the visual display was always presented with the visual object target images. For the auditory stimuli, a complex tone composed of three frequencies (200, 400 and 800Hz) with a deviation frequency of 50Hz was always presented with auditory object target sounds. Given that these stimuli were present in both intact and degraded conditions, we do not believe that their presence will systematically influence the results as the main contrast of interest was intact versus degraded performance.

bark for congruent; object stimulus and scrambled stimulus for neutral). On incongruent trials, there were 12 possible pairings given the stipulation that the distractor had to be an object from a different modality, (i.e., dog image could be paired with any of the three exemplars from the electronics, musical instruments, vehicles or tools categories). Thus, in order to retain equivalent stimulus uncertainty in the congruent and incongruent conditions (as well as the same stimulus–response mappings), a single random pairing was used for each incongruent item. For example, when dog was attended (in either vision or audition), it was always paired with a clock during incongruent trials.

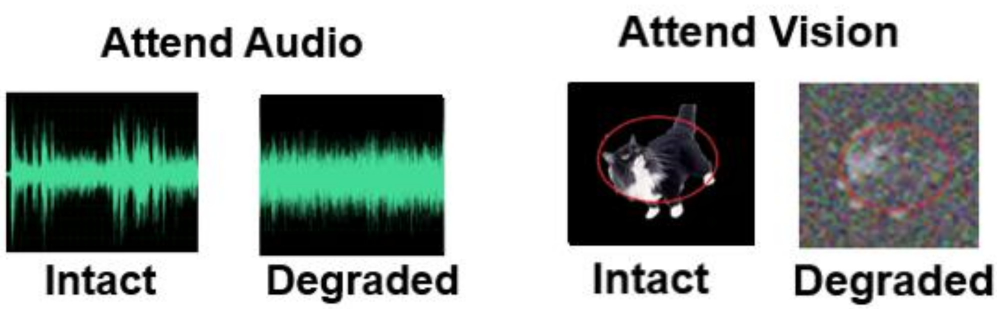


Figure 5. Example of stimuli used for intact and degraded conditions for attend–audition and attend–vision conditions. White noise was added to stimuli in both modalities to create the degraded conditions.

The design of the current experiment was a within–participants 2 (attended modality; audition, vision) by 2 (SD; intact, degraded) x 3 (congruent: congruent, incongruent, neutral) factorial design. All factors were orthogonally combined, leading to 12 conditions. Attended modality and SD were manipulated across blocks, resulting in four blocks; attend–audition – intact (AI), attend–audition – degraded (AD), attend–vision – intact (VI) and attend–vision – degraded (VD). In each block each object (collapsed across rotation for visual stimuli) was presented 12 times in the attended modality. Four of these presentations were paired with a congruent object in the unattended modality, four with an incongruent object in the unattended modality and four with a neutral object in the unattended modality. Given 12 presentations of each object in the attended modality by 15 objects in total, there were 180 experimental trials per block and 720 across the four blocks, leading to 60 observations per condition. Trial order was randomized per participant and block order and button–box response mapping was counter–balanced across participants.

During each block, participants were presented with an audio–visual object at each trial followed by a printed word. Participants were asked to decide if the printed word matched the object represented in the attended modality by pressing one button to indicate a ‘yes’ response and another to indicate a ‘no’ response.

Procedure

Following informed consent, participants were seated in a quiet and darkened room. They first completed the standard ANT (Fan et al., 2002). In this task participants were asked to focus on a centrally presented arrow, while ignoring flanking arrows (two flanker arrows on either side). Flankers could point in in the same (congruent trials) or opposite (incongruent trials) direction as the central arrow, or otherwise flankers were straight lines with no direction (neutral trials). Participants completed one block of the ANT which comprised 288 trials with 96 trials for each congruency condition. Once this was completed participants began the main experiment. Each participant completed 24 practice trials for each block type. For each block each trial began with a centrally presented fixation cross for 200 ms, followed by a blank screen for 50 ms. This was followed by an audio–visual object presented for 500 ms, a printed response cue then remained on screen until a response was made. Once a response was recorded, a 50 ms response checking period was followed by visual feedback in the form of a centrally presented green cross (correct trials) or a red cross (incorrect trials) for 500 ms. The response–stimulus interval was

800 ms (see Figure 6 for a schematic of the trial structure). Participants were asked to respond as quickly and as accurately as possible by pressing one of two horizontally arranged buttons on PsyScope Button Box. The entire experiment was completed in approximately 1.5 hours.

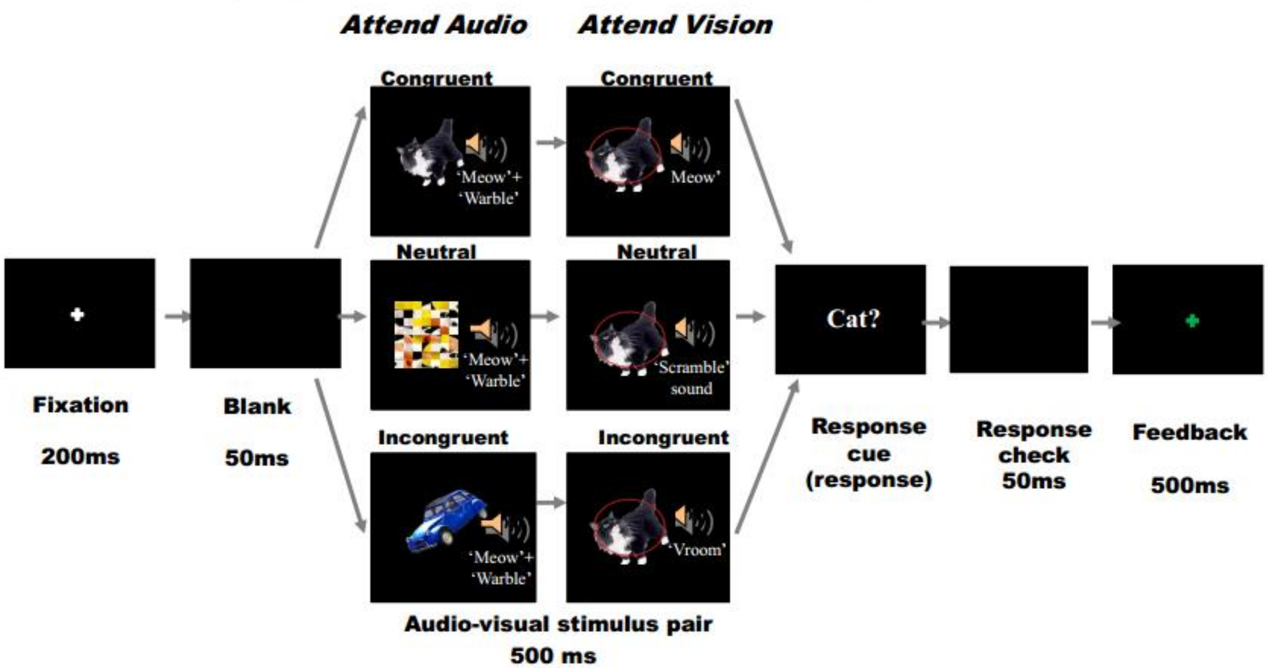


Figure 6. Schematic of the trial structure for attend–audition and attend–vision conditions.

Results

All analyses were carried out on median RT and percent error rates. Follow up tests were conducted with Tukey's HSD, $p < .05$.

Impact of SD on cross–modal distractor processing

SD manipulation check

To ensure that the degradation manipulation was successful and that degraded trials were slower and/or more errorful than intact trials, a 2 (modality; audition, vision) x 2 (degradation; intact, degraded) repeated measures ANOVA was conducted on RTs and percent error rates collapsed across all trial types (congruent, incongruent and neutral; see Figure 7).

RT data revealed a main effect of modality F (1,47) = 37.1, MSE = 530000, $p < .001$, η^2_p = .441, a main effect of degradation F (1,47) = 100.8, MSE = 1930000, $p < .001$, η^2_p = .682, and an interaction of modality and degradation F (1,47) = 8.5, MSE = 134000, $p < .05$, η^2_p = .154. The main effect of modality revealed slower RTs to auditory (802 ms) compared with visual (697 ms) responding. Importantly, the main effect of degradation revealed slower RTs to degraded (850 ms) compared to intact (649 ms) conditions. Post hoc tests revealed that the interaction between modality and degradation was due to the fact that while auditory responding (728 ms) was slower than visual responding (570 ms) in the intact condition, there was no difference between auditory (876 ms) and visual (823 ms) in the degraded conditions. This suggests that the degradation manipulation had a greater effect on vision, revealing that under degraded conditions, auditory and visual processing were roughly equated.

Error rate data mirrored RT data in a main effect of modality, F (1,47) = 17.6, MSE = .041 , $p < .001$, η^2_p = .273, revealing more errorful responding to audition (16.25%) compared to vision (13.32%). The critical main effect of degradation was also significant, F (1,47) = 467.2, MSE = .1.933 , $p < .001$, η^2_p = .909, revealing more errorful responding to degraded (24.82%) compared to intact (4.75%) conditions. The interaction between modality and degradation was non–significant F (1,47) = .024, MSE = .0006430 , $p = .877$, η^2_p = .001. Both RT and error rate data suggest that the SD manipulation was successful in that participants found the degraded trials more demanding than the intact trials.

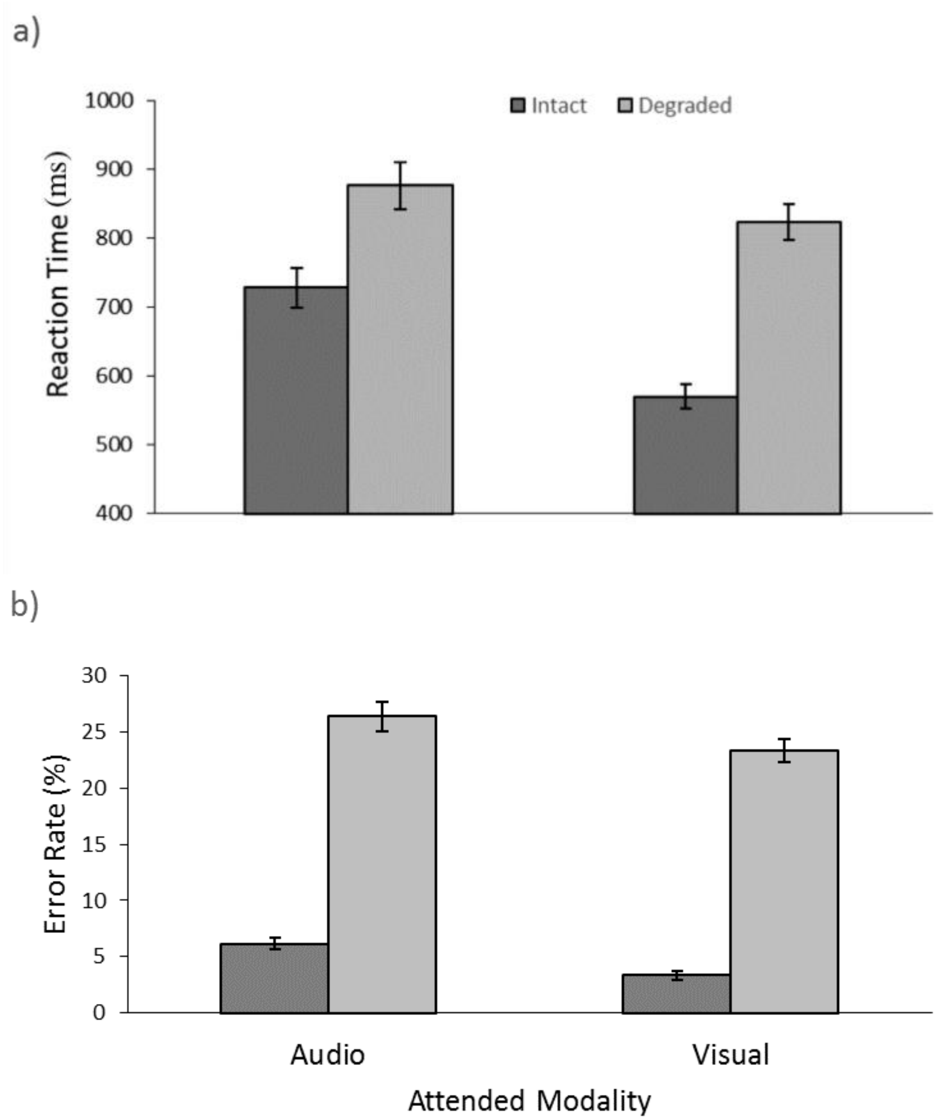


Figure 7. SD manipulation check. Overall performance collapsed across congruency in RT (a) and error rates (b) are shown for intact and degraded conditions for attend–audio and attend–vision modalities. Error bars represent standard error.

Distractor effects

A primary aim of the current study was to assess the impact of SD on distractor processing. Distractor scores were computed by subtracting performance on congruent trials from performance on incongruent trials. The distractor scores were then entered in a 2 (attended modality: audition, vision) x 2 (SD; intact, degraded) repeated measures ANOVA for both RT and percent error rate data (Figure 8a).

RT data showed a main effect of modality, F (1,47) = 30.18, MSE = 390 000, p < .001, η^2_p = .391, which revealed that greater distraction for attend–audition (149 ms) compared to attend–vision (59 ms) conditions. Neither the main effect of degradation, F (1,47) = .74, MSE = 7841 , p = .396, η^2_p =.015, nor the interaction between modality and degradation F (1,47) = .01, MSE = 102 , p = .909, η^2_p = .000, reached significance (see Figure 8a).

Similar to RT data, the error rate data revealed a main effect of modality F (1,47) = 30.18, MSE = 390000 , p < .001, η^2_p = .258, with more errorful responding on attend–audition (9.27%) compared to attend–vision (4.50%) responding. In contrast, the error rate date revealed a main effect of degradation, F (1,47) = 25.09, MSE = 1234 , p < .001, η^2_p = .348, such that degraded conditions (9.40%) were more susceptible to distraction than intact conditions (4.40%). The lack of interaction between modality and degradation F (1,47) = .30, MSE = 11 , p = .589, η^2_p = .006, suggests that degraded conditions suffered from greater distraction than intact trials during both attend–audio and attend–vision condition (see Figure 8a).

As addressed in the introduction, while distractor scores are often used in selective attention paradigms, one limitation of such scores is they do not provide any insights into whether the distraction stems from facilitation or interference, or a combination of both. In previous research on the effect of SD on cross–modal distractor processing, research revealed that increased distraction by irrelevant auditory information on visual target processing manifested in terms of interference but not facilitation (Yuval–Greenberg & Douelle, 2009). We were interested in attempting to replicate this finding and also determining if this pattern would be observed when the attended modality was audition, as previous research comparing uni–modal and cross–modal selective attention found different patterns of interference and facilitation based on the attended modality (Sinnet, Spence & Soto–Faraco, 2008). Thus, we also examined facilitation and interference effects.

Facilitation

Facilitation scores were calculated by subtracting performance on congruent trials from performance on neutral trials. Resultant facilitation scores for both RT and error rate data (Figure 8b) were entered into a 2 (attended modality: audition, vision) x 2 (SD; intact, degraded) repeated measures ANOVA.

The RT data revealed a main effect of modality, F (1,47) = 15.58, MSE = 77800, p < .001, η^2_p = .249, such that there was greater facilitation for attend–audition (78ms) compared to attend–vision (38 ms) conditions. All other main effects and interactions were non–significant (main effect of degradation, F (1,47) = 0.28, MSE = 2519 , p = .598, η^2_p = .006; interaction of modality and degradation, F (1,47) = 1.25, MSE = 5792 , p = .269, η^2_p = .026; see Figure 8b).

Error rate data also revealed a main effect of modality, F (1,47) = 5.69, MSE = 159.5 , p < .05, η^2_p = .108, such that there was greater facilitation for attend–audition (2.73%) compared to attend–vision (0.90%) trials. In addition, the main effect of SD was significant, F (1,47) = 18.35, MSE = 495.2 , p < .001, η^2_p = .281, with greater facilitation in degraded (3.42%) than in intact (0.20%) conditions. Finally, there was a trend for an interaction of degradation by modality, F (1,47) = 3.64, MSE = 94.9 , p = .063, η^2_p = .072. This trending interaction stemmed from the attend–audio degraded condition receiving more facilitation than all other conditions.

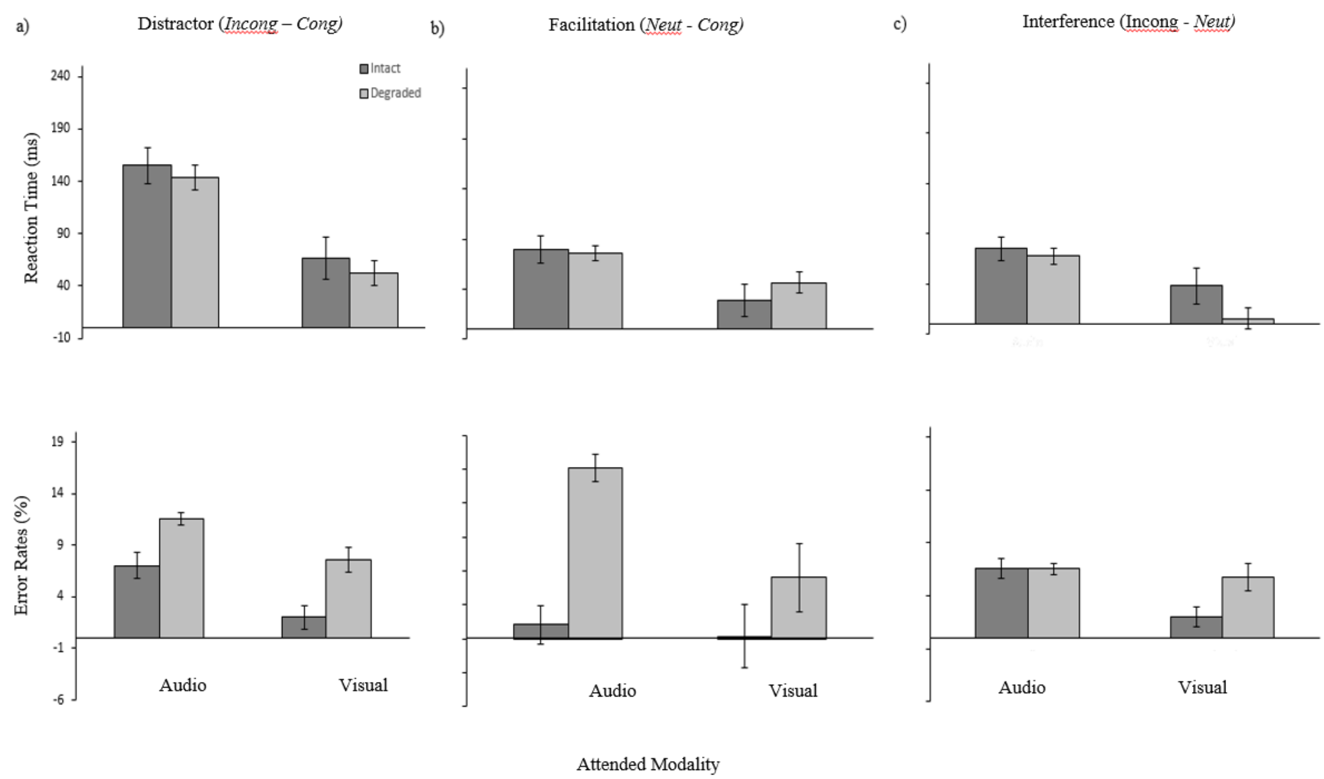


Figure 8. Reaction time and error rate data for distractor (a), facilitation (b) and interference (c) scores for each modality. Error bars represent standard error.

Interference

Interference scores were calculated by subtracting performance on neutral trials from performance on incongruent trials. Resultant interference scores for both RT and percent error rate (Figure 8c) data were entered into a 2 (attended modality: audition, vision) x 2 (SD; intact, degraded) repeated measures ANOVA.

The RT data revealed only a main effect of modality, F (1,47) = 15.93, MSE = 119000, p < .001, η^2_p = 2.53, again showing greater interference attend–audio (72 ms) than attend–vision (21 ms) trials. Non–significant effects of degradation (F (1,47) = 2.78, MSE = 19300 , p = .102, η^2_p = .056) and of the interaction between modality and degradation (F (1,47) = 1.32, MSE = 7431 , p = .256, η^2_p = .027), were found (see Figure 8c).

Error rate data revealed a significant effect of modality (F (1,47) = 7.04, MSE = 347.6 , p < .05, η^2_p = .103), a main effect of degradation (F (1,47) = 4.21, MSE = 165.6 , p < .05, η^2_p = .082), and an interaction between modality and degradation (F (1,47) = 4.30, MSE = 171.9 , p < .05, η^2_p = .084). The interaction between modality and degradation shows that although overall audition (6.58%) received more interference than vision (3.89%), and degraded (6.16%) received more interference than intact (4.31%), degradation only impacted distractor processing in attend–vision conditions. Specifically, post–hoc analysis showed no significant difference in the amount of interference observed between attend–audio intact (6.60%) and degraded (6.56%) conditions. However, there was a significant difference in the amount of interference observed between attend–vision intact (2.01%) and attend–vision degraded (5.76%) conditions (see Figure 8c).

While both RT and error rate data reveal that RT data revealed that overall audition was more susceptible to interference and facilitation by visual distractors, than vice versa, the impact of degradation differentially impacted facilitation and interference scores in the error rates based on attended modality. Specifically, degradation led to greater facilitation by visual distractors on auditory targets, while degradation led to greater interference effects by auditory distractors on visual targets. This finding highlights the importance of designs in which both vision and auditory serve as targets and distractors, as the attended modality impacts the observed patterns of distraction under degraded conditions (See also, Jacoby, Hall, & Mattingley, 2012).

The impact of processing efficiency

In line with previous work (e.g., Yuval–Greenberg & Douelle, 2009) we find evidence for visual dominance as attend–audition conditions tended to receive more distraction than attend–vision conditions, indexed by a main effect of modality in both RT and error rate data for distraction, facilitation and interference scores. As discussed in the introduction, if the visual advantage observed in the current study for object processing was due to vision being faster than audition and thus influencing auditory targets to a greater degree, then we may expect to find a correlation between the relative speeds of vision and audition and distractor effects in the intact condition.

To address this question, a processing efficiency (PE) score for RT and errors was computed for attend–audio and attend–vision conditions. PE scores were obtained by subtracting performance on a visual bimodal baseline condition which consisted of naturalistic image paired with a scrambled neutral sound, from performance on an auditory bimodal baseline condition which consisted of a naturalistic sound paired with a neutral image. A single PE score was calculated for both the attend–audition and attend–vision intact conditions, as in both of these conditions participants were presented with an intact target and an intact distractor. The intact PE score was calculated by subtracting performance on intact–neutral visual trials from intact–neutral auditory trials. For the degraded conditions, a separate PE score was calculated for attend–vision and attend–audition. This was because in the attend–vision degraded condition participants were presented with a degraded visual stimulus and an intact auditory stimulus. Thus the PE score was calculated by subtracting performance on degraded–neutral visual trials from performance on intact–neutral auditory trials. Conversely, for attend–audition degraded conditions, participants were presented with a degraded auditory stimulus and an intact visual stimulus and so the PE score was calculated by subtracting performance on intact–neutral visual trials from degraded–neutral auditory trials. Correlations were computed using Pearson's *r* and Bonferonni corrections were applied for multiple comparisons (see Table 2 and Figure 9 for graphical representation).

Distractor correlations

Correlations between intact PE RT scores and intact distractor RT scores showed a significant positive correlation in the intact attend–audio (AI) condition (*r* = .47; see Figure 8a) but not in the intact attend–vision (VI) condition (*r* = –.17; see Figure 8b). Similarly, degraded PE RT scores and attend–audition degraded distractor RT scores showed a significant positive correlation (*r* = .62) while no significance was found for the attend–vision degraded condition (*r* = .06). For the error rate correlations, no significant correlations were found between distractor scores and intact (attend–audio *r* = .35; attend–vision *r* = –.24) or degraded (attend–audio *r* = .20; attend–vision *r* = –.23) PE scores.

Significant correlations were only found in the attend–audio conditions in RT data. These correlations were in line with a processing efficiency account of the observed modality dominance as they suggest that the faster vision was relative to audition, the greater the impact visual distractor had on auditory processing in intact conditions.

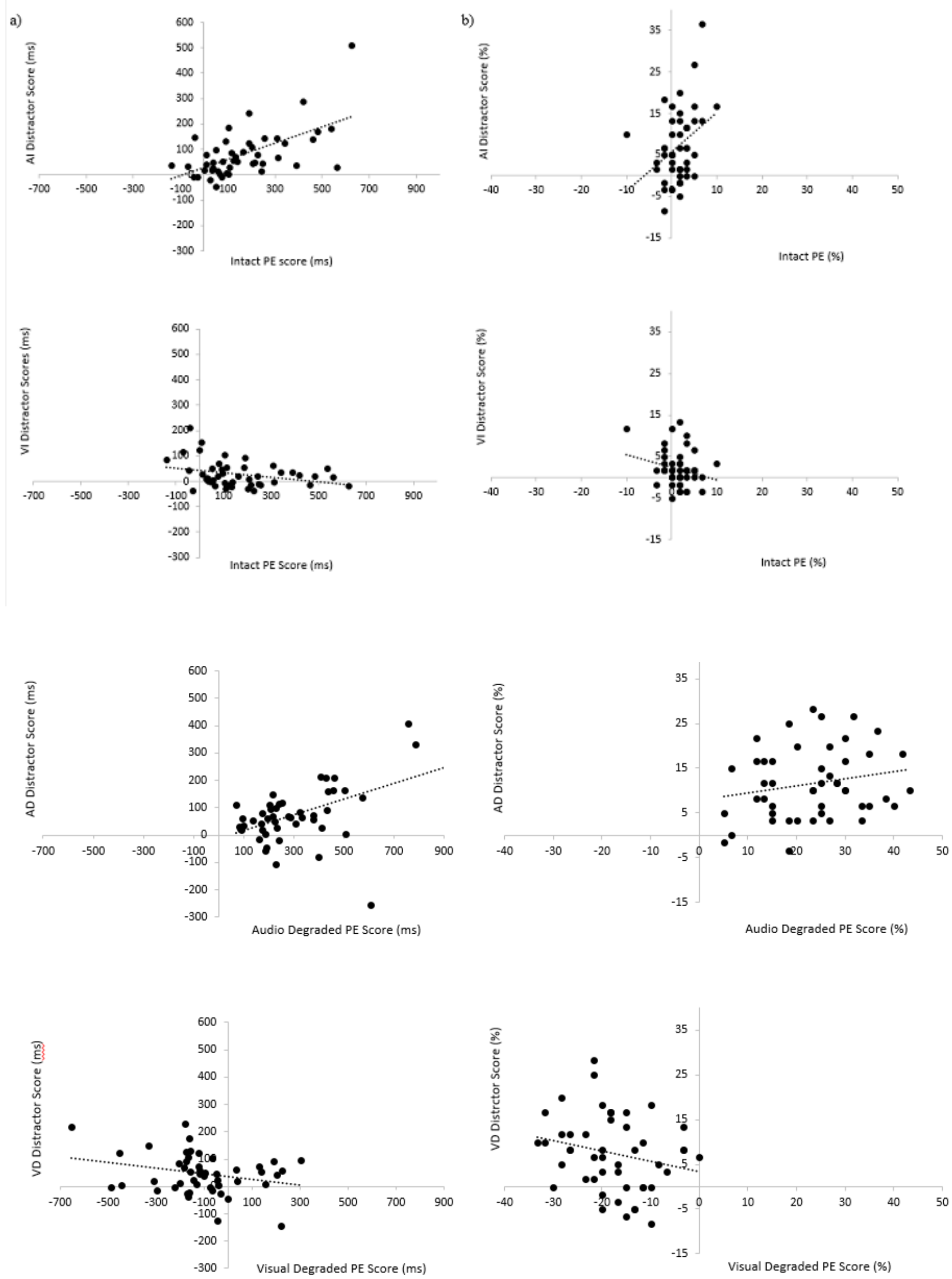


Figure 9. Correlations between distractor scores for audio intact (AI), audio degraded (AI) visual intact (VI) and visual degraded (VD) conditions with PE scores, for RT (a) and error rates (b)

Table 2. Pearson's *r* correlations. Correlations between processing efficiency and distractor scores are shown below for attend–audition intact (AI), attend–audition degraded (AD), attend–vision intact (VI) and attend–vision degraded (VD). For all PE scores, performance on visual baseline conditions was subtracted from performance on auditory baseline conditions (AI and VI PE scores = AI – VI; AD PE scores = AD –VI; VD PE scores = AI – VD)

		AI		AD		VI		VD	
		RT	Errors	RT	Errors	RT	Errors	RT	Errors
Distractor Correlations	*r*	***.47***	***.35***	***.62***	*.21*	*–.17*	*–.24*	*.06*	*–.22*
	p	*.001*	*.015*	*<.001*	*.162*	*.248*	*.105*	*.650*	*.128*

ANT correlations

Error rate data showed a trending effect for correlations between the ANT score and the main task in the attend–vision degraded condition ($r = .279$, $p = .058$), with all other conditions failing to show any significant effects (all *p*s> .251). The lack of any significant correlations between participants' selective attention performance on the ANT and the current task suggests that uni–modal visual and cross–modal selective attention do not rely on similar cognitive mechanisms.

Discussion

The current study has four main findings. First, we replicated previous findings of visual dominance in object perception. Second, with our orthogonal design in which we examined the impact of SD on both attend–audio and attend–vision conditions, we found opposite patterns of interference and facilitation effects during SD, based on the target modality. Third, there was some support for a processing efficiency account of the observed visual dominance, however this was only significant for attend–audition conditions. Finally, the lack of any significant correlations between a uni–modal visual selective attention task (ANT) and the current findings suggests that there are important differences between uni–modal and cross–modal selective attention abilities. Each of these findings will be discussed in greater detail below.

Previous investigations of object recognition have shown that vision tends to dominate object perception during intact stimulus presentation, evidenced by greater interference by irrelevant visual information on auditory object processing than vice–versa (Yuval–Greenberg & Douelle, 2009). However, these authors found that when the visual input was degraded, the influence of auditory distractors increased, suggesting visual dominance in object processing is somewhat flexible. In the current study we showed that participants were more errorful on incongruent versus congruent trials, and that this effect was stronger in degraded than in intact trials. Furthermore, when looking at the attend–vision conditions in the current study and examining the separate effects of facilitation and interference, like Yuval–Greenberg and Douelle (2009) we found that only interference effects modulated based on SD. That is to say, that while interference effects increased from intact to degraded attend–vision conditions, there was no difference in the effects of facilitation during intact or degraded attend–vision conditions.

One novel aspect of the current study was to extend the findings of Yuval–Greenberg and Douelle (2009) by examining whether a similar modulation of distractor effects during the SD condition would manifest in terms of interference but not facilitation under attend–audition conditions. In order to do so we included an attend–audio condition in which the auditory target information was presented both intact and degraded. Overall the attend–audition conditions received more interference and facilitation than the attend–vision conditions, indexed by a main effect of modality in both RT and error rate data for interference and facilitation scores. Importantly though, the interaction of modality and degradation in error rate data revealed different patterns of facilitation and interference depending on the target modality. Specifically, while participants received significantly more interference during attend–vision degraded compared to attend–vision intact conditions, there was no difference in interference for auditory intact and degraded conditions. Conversely, while participants received significantly more facilitation on attend–audition degraded compared to attend–audition intact conditions, there was no difference in the amount of facilitation participants received for attend–vision intact or degraded conditions.

One potential explanation for the current results stems from a finding by Sinnett et al., (2008), where they showed that while vision benefits from the presence of a neutral auditory stimulus relative to a uni–modal visual only condition, audition actually experiences costs associated with the presence of a neutral visual stimuli over a uni–modal auditory only condition. Thus, given that in the current study our baseline condition was audio–visual, it may be the case that attend–vision did not see any facilitative effect in the congruent versus neutral condition because the neutral condition already, by nature of being multimodal, offered facilitation. Hence, there were no additional increases to the extent of facilitation based on the congruent identity of the auditory stimulus. However, when the identity of the auditory stimulus did not match, this led to interference effects such that there was a cost that was not present in the neutral or congruent conditions. Similarly, since audition receives interference from the presence of a visual stimulus there was no additional interference based on the incongruent identity of the visual stimulus. However, when this additional visual stimulus was congruent, there was a facilitation effect that helped to negate the costs associated with the presence of an incongruent or neutral visual stimulus. This explanation must be investigated empirically in future research, as in the current study we did not have a uni–modal baseline condition by which to confirm that audio–visual presentation is beneficial relative to visual only and costly relative to auditory only stimulus presentation.

Another novel aspect of the current study was the use of the neutral trials to obtain a processing efficiency score that allowed us to determine the relative processing speed of audition and vision in absence of distractors. This allowed us to determine if visual dominance in object recognition is based on modality appropriateness (Welch & Warren, 1980) such that vision is the more suited modality for this type of processing, or if the observed visual dominance is more simply due to objects being processed faster in the visual compared to the auditory modality. To do this, we correlated our processing efficiency scores with distractor scores to determine if those individuals showing less efficient processing on auditory compared to visual neutral trials were also more likely to see greater distraction by vison than by audition. Significant correlations of processing efficiency and distractor scores were in line with a processing efficiency account of visual dominance, such that those individuals who had larger discrepancies between auditory and visual processing, with audition being slower/more errorful, also showed stronger effects of visual distraction and weaker effects of auditory distraction. While this effect was only significant in the attend–audition intact and attend–audition degraded (ER) conditions in RT data, visual inspection of all the correlation data (see Table 2) suggests that overall the data aligned well with a processing efficiency view. Specifically, while all auditory correlations were positive, all visual correlations, expect for the degraded RT data, showed negative correlations. Thus, overall data provide support for a processing efficiency account of the visual dominance observed in the current study.

Finally the current study found no correlations between participants' scores on the current task, and scores on the ANT task (Fan et al., 2002), the latter serving as a standard measure of selective attention abilities in a uni–modal visual paradigm. While we may not have expected to find any significant correlations in the degraded conditions, as here participants may have been intentionally widening their attentional scope to include the distractor modality (e.g., Meredith &

Stein, 1983), we may have expected to find significant correlations in the intact conditions based on previous reports (Forster & Lavie, 2007). Thus the lack of any significant correlations between intact conditions and the ANT task was unexpected. One potential explanation is that given the use of naturalistic stimuli, as well as spatial and temporal correspondence in both the intact and degraded conditions, the likelihood for integration was also strong in the intact conditions, and thus preventing distraction may have much more difficult in this condition than the ANT task. Thus, in the same manner that success in selective attention abolished individual differences, as evidenced by the high perceptual load condition of Forster & Lavie, (2007), large failures in selective attention may also eliminate or reduce individual differences. However, given the limited support for large differences in overall distraction in the intact condition of the main distractor task and the ANT task in ER data (4.5%, ANT = 1.8%) and RT data (main task = 110ms, ANT task = 93ms) it is unlikely that the intact condition in the main task led to a large failure of selective attention. Furthermore, in a previous study in our laboratory (thesis Experiment 1; Sandhu & Dyson, in press), we did find correlations between the ANT task and our distractor measure in attend–audio conditions, and in this task the stimuli were identical. However, in this previous study, the differing effects of facilitation and interference by target modality were not present, potentially due to weaker overall distractor effects. Thus, one explanation is that given vision is only experiencing interference, and audition is only experiencing facilitation, correlations are not significant using an overall distractor score. While the ANT does include a neutral condition, this is not reliably different from the congruent condition and thus overall distraction father than facilitation and interference is the most reliable measure in the ANT task (Fan et al., 2002), preventing a comparison of facilitation and interference scores across the main task and the ANT. Furthermore Sandhu and Dyson (in press) only found correlations between the ANT and the main task in attend–audio conditions, leading to the conclusion that selective attention relies on a different control mechanism in uni–modal and cross–modal selective attention. This is supported by the lack of any significant correlations between the main distractor task and the ANT task in the current study, in addition to previous work which has also failed to find patterns of perceptual load effects on selective attention which are very reliable in the uni–modal visual literature in paradigms using a cross–modal design (e.g., Jacoby, Hall & Mattingley, 2012; Muller–Gass, Stelmack & Campbell, 2006; Parks, Hilimire, & Corballis, 2011; Rees, Frith, & Lavie, 2001, Experiment 2; Tellinghuisen & Nowak, 2003; Vroomen, Driver & De Gelder, 2001).

Overall the current findings replicated previous work by showing that visual dominance is fluid and can be reduced by degrading the quality of the visual input. In addition the current findings extended on previous work by showing that degrading auditory stimuli also increases distraction for auditory targets. Interestingly, while both audition and vision show greater distraction in degraded conditions, this manifests as increased interference for visual targets, and increased facilitation for auditory targets. That the pattern of results is different for each modality, adds to previous work that shows that the same manipulation can have differing effects on auditory and visual attention (Jacoby, Hall & Mattingley, 2012; Sinnett, Soto–Faraco & Spence, 2008) and highlights the importance of orthogonal research designs. We also show that processing efficiency provides a strong account for visual dominance in the current study. Finally our correlational analysis with the ANT task adds to a growing body of literature that suggests that there are differences in uni–modal and cross–modal selective attention.

Chapter 4: Experiment 3. The impact of PL and SD on cross–modal distractor processing

Abstract

Uni–modal selective attention is differentially impact by increases in PL and SD, such that the former improves while the later deteriorates the success of selective attention. This is thought to be due to increases in PL representing capacity limits, while increases in SD represent a data limit, with additional processing resources being applied to the target during capacity but not data limited conditions. The current study sought to investigate if such differences in capacity and data limits would also be present during cross–modal selective attention, with three specific aims. First, a single manipulation was used to create capacity limited and data limited conditions within a single experiment, whereas previous research has used different methods of increasing PL and SD thus introducing potential confounds. Second, cross–modal selective attention was assessed when both audition and vision served as the target modality. Third, in addition to using a compatibility measure of selective attention, a detection measure was also used to provide a more liberal measure of modulations in selective attention. Both the PL and the SD conditions were created by asking participant to decide which of two arrows (attend–vision) or two sounds (attend–audition) was longer, the one going '*up*' or the one going '*down*'. Compatibility was manipulated by having congruent or incongruent directions represented in the distractor modality, and detection was manipulated by added a burst of noise into the distractor modality on 50% of trials. The data from this study revealed that in contrast to uni–modal selective attention, there were no differences between capacity and data limited conditions, with trends for increased distraction in both conditions. The results are discussed in terms of differences between uni–modal and cross–modal selective attention mechanisms.

Introduction

In our everyday experience, we are presented with a multitude of sensory information at any given time, and only some of this information is relevant to our current goals. Selective attention, the ability to attend to a subset of incoming perceptual information, is a mechanism that allows us to prevent sensory overload. Although selective attention is a very important mechanism for daily functioning, it is not always successful (e.g., Eriksen & Eriksen, 1974; Gatti & Egeth, 1978; Stroop, 1935). Various factors are thought to influence the success of selective attention, including PL and SD.

Lavie (1995) proposed PLT to consolidate a large literature of selective attention which showed support for both early and late selective attention mechanisms (see Driver 2001 for a review). The two main tenets of PLT are that there is a capacity limit in terms of the amount of available processing resources, and that all resources will be used up to the capacity limit. The result is that tasks which do not reach a capacity limit in terms of resources required for processing (LL tasks) are *obligatorily* transferred to the processing of non–target information, while those tasks that are more demanding led to the capacity limit being reached (HL tasks) and result in the reduced influence of non–target information.

Similar decreases in processing efficiency that are seen in HL conditions can also occur under conditions of SD. That is to say, both load and degradation manipulations led to longer RTs and higher error rates. However, when processing is made less efficient by a degraded sensory signal, the impact of distracters actually *increases* (e.g., Ben–David & Schnieder, 2010; Yuval–Greenberg & Douelle, 2009). Thus, Lavie expanded load theory to include the critical notion that the effects of increased PL are not the same as SD effects (Lavie & De Fockert, 2003). To dissociate the two, Lavie claimed that PL effects are those in which HL conditions require additional processing due to additional stimuli that presented, or more difficult perceptual distinctions that need to be made on the target information (Cartwright–Finch & Lavie, 2007; Macdonald & Lavie, 2011). These specific factors cause capacity limits to be reached and reduce the influence of irrelevant stimuli. The genesis of Lavie's distinction between PL effects and SD effects on selective attention comes from an early theory put forth by Norman and Bobrow (1975), in which the authors propose a difference in capacity and data limited processing. According to this distinction, capacity limits are concerned with the amount of processing resources available for target processing, while data limits are concerned with the quality of the information provided by sensory signals. Crucially, it is thought that limitations surrounding the quality of information (data limit) cannot be compensated for by increasing resource allocation to the target stimulus. Thus according to Norman and Bobrow, as a capacity limit is reached, all available resources are directed toward processing of the target stimulus. A consequence of this is that no processing resources remain for distractor information, and thus, in line with Lavie's load theory, a HL (capacity limited) condition should see less distraction than a LL condition. However, since data limits cannot be compensated for by placing additional resources towards the processing of the target information, then it stands to reason that these resources are directed towards other non–target stimuli, thus causing an increase in distractor processing during SD. Further support for a neurological distinction between data and capacity limited processing comes from a study by Han and Marois (2011), in which the authors showed that parieto–frontal networks typically involved in attention are recruited by manipulations of capacity limits but not by data limits.

Thus, there seems to be support in favour of differing effects of data and capacity limitations on selective attention performance. However, the few studies that have directly contrasted these effects have found mixed results. Lavie and de Fockert (2003) examined whether PL and SD would differentially impact uni–modal visual selective attention. The authors used a target search task in which they manipulated the number of non–targets amongst the target to yield HL (several non–targets) and LL (target in isolation) conditions. In addition, in the LL condition, SD was manipulated by presenting poor quality targets that were smaller and of lower contrast compared with intact targets (Experiment 1) or had reduced presentation duration compared to intact targets (Experiment 2). Using the low–load intact condition as the baseline, the authors found that the low–load degraded condition led to increased distractor effects, while the high–load condition led to decreased distractor effects, supporting the notion that data limits led to an increase in distraction while capacity limits led to a decrease in distraction. In contrast, a more recent study by Benoni and Tsal (2012) that used a similar paradigm to Lavie and de Fockert (2003) found that the direction of PL effects could be modulated by dilution. Specifically, Benoni and Tsal (2012: see also Benoni & Tsal, 2010; Tsal & Benoni, 2010a, 2010b; Wilson, Marois & MacLeod, 2011) argued that dilution effects occur when the activation of the distractor is dampened in the presence of non–target items, which are also activated during search for the target. In Lavie and de Fockert's (2003) LL SD condition, the target was presented in isolation, while in the HL condition it was presented amongst non–distractor items. Thus, Benoni and Tsal (2012) suggest that the differential effects of PL and SD obtained by Lavie and de Fockert (2003) need not reflect a dissociation between capacity and data limits respectively, but instead can be attributed to dilution of the distractor by non–targets in the HL condition, leading to decreased distractor processing, and no dilution in the SD condition, leading to increased distractor processing. In support of this notion, Benoni and Tsal (2012) found both increased load and increased SD led to increased distractor effects in the absence of diluting stimuli whereas they both led to decreased distractor effects in the presence of diluting items.

While there remains controversy over the adequacy of a dilution account of PL effects (see commentary between Tsal & Benoni, 2010a, b, and, Lavie & Torralbo, 2010), the conflicting results obtained by Lavie and de Fockert (2003), and, Benoni and Tsal (2012) highlight potential problems with using set size as a PL manipulation. Another concern in Experiment 2 of Lavie and de Fockert (2003) is the potential speed accuracy trade–off in the HL relative to the degraded LL condition. Specifically, RTs were significantly greater, but error rates (ER) significantly smaller in the HL (RT = 651 ms; ER = 7%) compared to LL degraded condition (RT = 601 ms; ER = 20%), rendering subsequent differences in distractor processing difficult to interpret.

To further complicate the direct comparison of PL and SD effects, studies of PL effects have used what are typically considered SD manipulations (e.g., Handy, Soltani & Mangun, 2001; Handy & Mangun, 2000) and have found effects in line with the predictions of PLT. For example, Handy et al. (2001) manipulated PL by altering the signal–to–noise ratio of the target stimulus by presenting HL targets for shorter durations and with masks at the target location. Altering the signal to noise ratio is typically a manipulation used for SD, but here produced decreased distractor processing in line with HL performance. Similarly, Yi, Woodman, Widders, Marois, and Chun (2004) manipulated PL by adding noise to the target stimulus in the HL condition and this led to decreased distraction (cf., Lavie & de Fockert, 2003, Experiment 2) in the HL condition. Again, adding noise to the target is typically used as a method for SD, however here it produced distractor effects in line with HL manipulations.

As is clear from the review of literature above, there are no clear distinctions between PL and SD effects. As discussed by Benoni and Tsal, (2013) it does not seem possible to differentiate PL and SD manipulations based on an antecedent stimulus distinction, as they exist on a continuum. However, one potential way to delineate the two is by a post–hoc examination of performance. As discussed in Madden and Langley (2003), evidence for data–limited processing can be gleaned by high error rates, and they suggest that tasks in which participants are making errors on 20% to 25% of trials are more representative of data limits than of capacity limits. This distinction is supported in the literature, where PL manipulations typically result in error rates below 10% (e.g., Lavie, 1995; thesis Experiment 1), and SD manipulations in error rates greater than 20% (thesis Experiment 2; Lavie & de Fockert, 2003). With this reasoning, it should be possible to use the same manipulation to promote both data and capacity limited processing. One advantage of doing so is that the studies that have directly contrasted data and capacity limits, by the nature of the specific manipulations have other differences in the HL and SD conditions that may impact distractor processing. For example, Yeshurun and Marciano (2013) point out that typical manipulations of SD (addition of noise, addition of a mask, reduced contrast) have the indirect consequence of decreasing target salience relative to distractor salience, while typical increases in PL (increased set size, singleton vs conjunction searches) do not impact the relative salience. As such it may be the case that increased distractor processing during data limited processing may be due to decreased salience of the distractors relative to the target, although there is mixed support for this in the literature. Thus, in the current study, we aimed to use a single manipulation to promote capacity and data limited processing. Specifically, participants were asked to distinguish between the length of two lines or the duration of two sounds. One can imagine that large differences between the line lengths/sound durations should be associated with low PL, but as this difference becomes smaller but still above threshold, participants would approach a capacity limit (HL) and then at some point when the difference was just below reliable threshold the same manipulation could represent a data limit (SD).

In addition to using a single manipulation to promote capacity and data limits, the current study was also novel in that it examined cross–modal selective attention. The studies to date that have directly contrasted capacity and data limits have done so in the uni–modal domain. If processing resources are shared across sensory modalities, then we would expect a similar pattern of distractor effects to emerge under capacity and data limits as reported in the uni–modal literature, namely decreased distraction during HL (e.g. Macdonald & Lavie, 2011; Mulligan, Duke, & Cooper, 2007; Toro, Sinnett & Soto–Faraco, 2005; Haroush, Hochstein & Deouell, 2009; Dyson, Alain & He, 2005, Experiment 2; Sinnett, Costa, & Soto–Faraco, 2006, Experiment 1; Klemen, Buchel & Rose, 2009) and increased distraction during SD (e.g., Lavie & de Fockert, 2003). However, if there are independent processing resources for each modality, then we may expect to see a different pattern. Specifically, we would not expect to see any modulation of distractor processing by load (e.g., Parks, Hilimire, Corballis, 2011; Muller–Gass, Stelmack & Campbell, 2006; Rees, Frith, & Lavie, 2001, Experiment 2; Vroomen, Driver & De Gelder, 2001), as devoting more processing resources towards the target modality in the high versus LL condition would not have any influence on the amount of available resources remaining to process distractors in the second modality. In contrast under SD conditions we may see a similar pattern of results to that in unimodal conditions, namely, an increase in distraction in degraded compared with LL conditions. Specifically, since data limited conditions cannot be compensated for by allocating additional resources to target information, these resources are rerouted to distractor processing. In this respect, this rerouting may be considered an intentional widening of attentional scope which is supported theoretically in the cross–modal domain by the principle of inverse effectiveness which states that the likelihood of multimodal integration is greater when the incoming information is weak (inverse effectiveness; Meredith & Stein, 1983) and is supported empirically in the literature by observations of increased distraction under degraded conditions (e.g., Yuval–Greenberg & Douelle, 2009). Furthermore, in the cross–modal domain, there is much evidence to suggest that when one modality is degraded there is a re–weighting of sensory information towards the non–degraded modality (e.g., Ernst and Banks, 2002). Thus, in the case of SD, even under conditions of independent resources for each modality, we may expect to see an increase in distraction as there will be a re–weighting of incoming information in favour of the non–degraded (and in the current study, the distractor) information. However, one lingering issue with the claim of independent resources across modalities is their reliance on null results, in which there is no difference in distractor processing across low and HL conditions. However, a potential strength of the current study is the potential for a finding of no differences in distractor processing based on PL manipulation but the finding of an increase based on a SD manipulation. Such a finding in a single experiment in which the same manipulation is used to promote capacity and data limited processing, could alleviate concerns that the null results in the PL condition are due to the nuances of the experimental design.

As the current study is concerned with cross–modal selective attention, one central question is whether resources are shared or independent across modalities. As such, it is important to have a strong test of independence and the final aim of the current study was to extend the traditional examination of differences in distraction based on compatibility effects which require identification of distractors (thesis Experiments 1 and 2) with the simple detection of distractors. Given that compatibility effects rely on a semantic match (congruent) or mismatch (incongruent) of the target and distractor stimuli, both the target and the distractor must be processed to the semantic level in order for such mis/matches to occur. Early selection theories of selective attention suggest that all incoming information is processes at the perceptual level, but that only selected information is further processed at the semantic level (e.g., Broadbent, 1958; Treisman, 1960). Thus, it may be that distractors are still being processed in the HL conditions, but are not impacting compatibility. For example, the irrelevant information may be detected but its object code is not activated, such that it fails to interfere with incongruent prompts nor facilitates congruent prompts in relation to the task–relevant visual information. This concern has been alleviated in the uni–modal visual literature, as studies relying on implicit processing of distractor stimuli have shown equivalent patterns to those studies which have employed distractor compatibility effects, namely, decreased distractor processing under HL conditions (e.g., Jiang & Chun, 2001; Lavie & Fox, 2000; Cartwright, Finch & Lavie, 2007; Reese, Frith & Lavie, 1997; Handy & Mangun, 2000). While there have been some studies which have looked at detection measures of distractor processing in the cross–modal domain, the results have been mixed with some studies finding support for decreased detection under HL (Raveh & Lavie, 2015; McDonald & Lavie, 2011; Parks, Hillmire & Corballis, 2009) but some studies finding no difference in detection across load conditions (Parks, Hillmire & Corballis, 2011). Furthermore, to our knowledge, no study has systematically tested the effects of SD on distractor detection under conditions of cross–modal selective attention. Finally, the effects of compatibility and detection have not been directly contrasted in studies examining the impact of PL and/or SD under conditions of cross–modal selective attention. Although a recent study by

Raveh and Lavie (2015) included both compatibility and detection measures, the authors only report the results of the detection measures.

Method

Participants

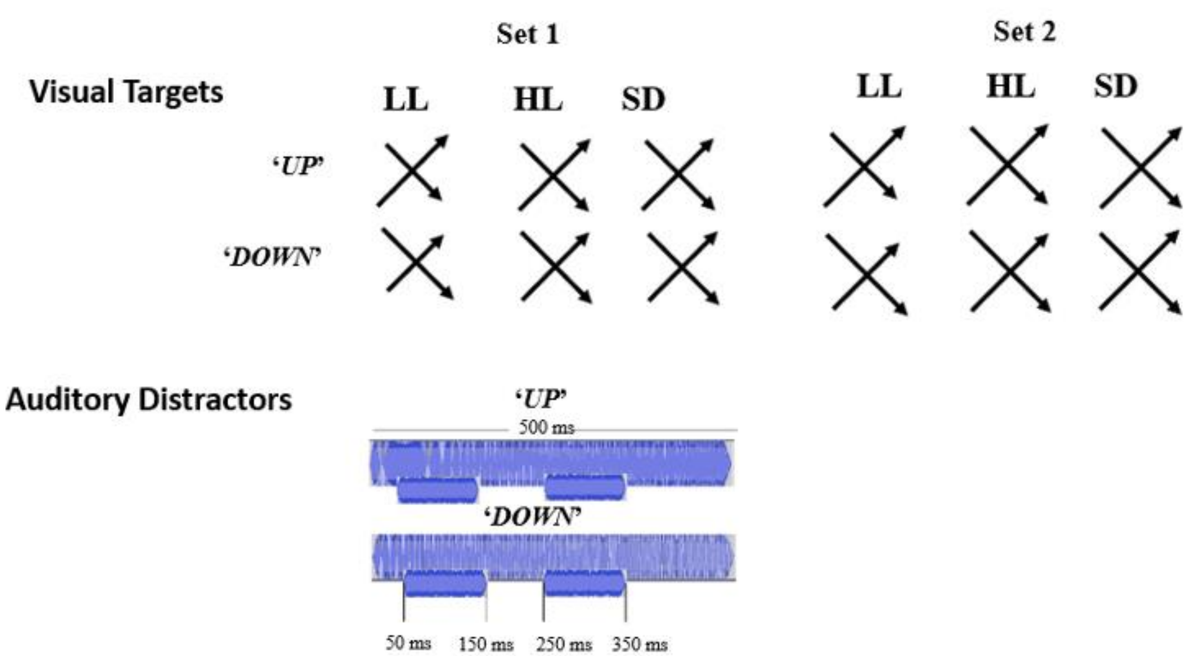
Forty–eight healthy adults (32 females; 39 right handed) from Ryerson University and the surrounding community participated in the study for course credit. The mean age was 28 years (age range 18–42 years). Two participants who were excluded due to an error rate of greater than 30% across all conditions were replaced with two new participants.

Stimuli and Design

Visual target stimuli consisted of two arrows of different length arranged in an 'x' with one arrow pointing up and the other pointing down. Two sets of visual target stimuli were created to ensure enough variability across trials, such that participants would use perceptual processing to make their response, rather than post–perceptual processing related to memory. In the first set of visual target stimuli the length of the longer arrow in set one was always fixed at 4.5 visual degrees, accompanied by one of three sizes of shorter arrows at 3.7, 4.1 and 4.4 visual degrees. In the second set, the length of the longer arrow was set at 3.5 degrees, and was accompanied by one of three sizes of shorter arrows at 2.7, 3.1 and 3.4 degrees. Visual target stimuli were presented in either a uni–modal or cross–modal condition. In the uni–modal condition, the visual target stimuli was accompanied on half of the trials with a one cm square of white noise (12% created using Photoshop CS4 software), hereafter referred to as the visual detection stimulus. The visual detection stimulus could appear three cm either to the left or right of the visual target stimulus. In the cross–modal condition, the visual target was always accompanied by auditory distractor stimuli which consisted of a 500 ms tone that either increased in pitch from 1000 Hz to 1167 Hz or decreased in pitch from 1000 Hz to 833 Hz. In addition, on half of the trials, embedded within the auditory distractor was a 100 ms white noise burst that began either 50 or 250 ms into the auditory distractor tone and was presented at –33 gain (created using the gain function in Audacity software) relative to the distractor tone. This auditory noise burst will hereafter be referred to as the auditory detection stimulus.

Auditory targets consisted of two tones played at the same time, with one tone increasing in pitch and the other decreasing in pitch with all tones having an initial pitch of 1000 Hz. One of the tones was always longer in duration than the other. Again two sets of auditory target stimuli were created with the longer tone in set one having a duration of 750 ms that either increased to 1250 Hz or decreased to 750 Hz. The long 750 ms tone was paired with one of three shorter auditory tones that had a duration of 450 ms (pitch increase to 1150 Hz or pitch decrease to 850 Hz), 550 ms (pitch increase to 1183 Hz or pitch

a)



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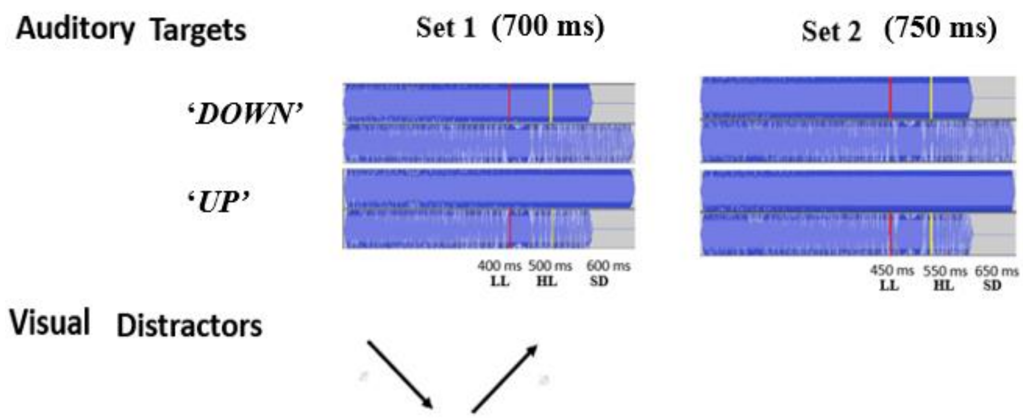


Figure 10. Auditory and Visual Target and Distractor stimuli across LL, HL and SD conditions for Attend–vision (a) and Attend–audition (b) blocks. For the auditory distractors, the noise burst was presented at either 50 ms or at 250 ms. For the auditory targets, the shorter sound in the SD condition is displayed alongside the long sound. The red lines represent where the shorter tone ended for the LL condition, and the yellow for the HL condition. For the visual distractors, the noise burst could appear either at the left or right of the arrow point up or the arrow pointing down. Uni–modal visual stimuli consisted of the visual targets with the noise burst displayed for the visual distractors. Uni–modal auditory stimuli consisted of the auditory targets, with the noise burst displayed for the auditory distractor.

decrease to 817 Hz) or 650 ms (pitch increase to 1217 Hz or pitch decrease to 783 Hz). In the second auditory target stimulus set, the long tone was fixed at 700 ms (pitch increase to 1233 Hz or decrease to 767 Hz) and was paired with one of three shorter auditory tones that had a duration of 400 ms (pitch increase to 1133 Hz or decrease to 867Hz), 500 ms (pitch increase to 1167 Hz or 833 Hz) or 600 ms (pitch increase to 1200 Hz or decrease to 800 Hz). Again auditory target stimuli were presented in uni–modal and cross–modal conditions. In the uni–modal condition, on half of the trials the auditory target stimulus was accompanied by the auditory detection stimulus. In the cross–modal condition the auditory target stimulus was always paired with a visual distractor that consisted of a single centrally presented arrow with a length of 3.5 cm, and the arrow pointed either up or down. On half of the trials the visual arrow distractor was accompanied by the visual detection stimuli (see Figure 10, for examples of the stimuli).

All auditory stimuli were created using Audacity software, intensity normalized and included 10 ms onset and offset ramps to avoid sample click. Loudness measured by a Scosche SPL 1000 sound level meter ensured that auditory stimuli were all presented at approximately 78 dB(C). Auditory stimuli were presented via Harman/Kardon speakers placed approximately 25 inches apart, on either side of a 24 inch iMac monitor on which visual stimuli were presented. All visual arrow stimuli were created using PowerPoint software, and were presented in the centre of the 24 inch iMac monitor, and were black presented on a white background. Participants were seated in a quiet, darkened room approximately 57 cm from the computer monitor. All stimuli were presented using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) and participants' speed and accuracy in responding was recorded by a PsyScope button box.

Difficulty was manipulated across blocks for both cross–modal and uni–modal conditions by varying the degree of difference between the longer and shorter stimuli in the attended modality. There were three levels of difficulty: a LL/intact (LL) condition not intended to be difficult enough to approach either a data or a capacity limit, a HL created to approach a capacity limit, and the final most difficult condition was created to impose a data limit and thus was considered a SD condition.

In addition to difficulty, congruency was also manipulated within cross–modal conditions. In the main target task, participants were asked to report if the longer arrow (in attend–vision conditions), or tone (in attend–audio conditions) was the one that was going ‘up’ or the one that was going ‘down’ in space or pitch, respectively. Congruency was thus manipulated by having the distractor stimulus going in the same (congruent) or opposite (incongruent) direction as the longer aspect of the target stimulus. For example, in an attend–vision condition if the longer arrow was pointing up, then a congruent case would be one in which the auditory distractor tone was also going up and an incongruent case would be one in which the auditory distractor tone was going down.

The design of the current study was a within–participants 2 (task type: uni–modal, cross–modal) x 2 (attended modality: audition, vision) by 3 (difficulty: LL, HL, SD) by 2 (congruency: congruent, incongruent) design. Task type, attended modality and difficulty were orthogonally combined and each factor was manipulated across blocks, resulting in 6 uni–modal blocks (U) and 6 cross–modal blocks (C); attend–audition – LL (UAL and CAL), attend–audition – HL (UAH and CAH), attend–audition – SD (UASD and CASD), attend–vision – LL (UVL and CVL), attend–vision – HL (UVH and CVH) and attend–vision – SD (UVSD and CVSD). In each block the two target stimuli (longer going up or longer going down) were presented 32 times each, and on half of these trials the distractor was congruent (16) and the other half was incongruent (16). For each target congruency relationship, half the trials (eight) had the detection stimuli present, and the other half did not contain the detection stimuli. Thus, there were 64 trials per block.

Trial order was randomized for each block per participant and block order was randomized across participants. Since the orientation of the button–box mapped to the response (press the button on top if the longer stimulus was going up, and the button at bottom if the longer stimulus was going down) mapping was held constant for all participants. Furthermore, since there were two responses, which stimuli was longer, and was the detection stimuli present or absent, all participants were asked to respond to the detection stimuli with their left index finger, and the target stimuli with their right index finger for an up response, and their right middle finger for a down response.

In addition a control block for the detection task was created for both attend–audio and attend–vision conditions. This block was identical to the UAA and the UAV blocks, with the exception that participants were not asked to make the target stimulus discrimination and were explicitly instructed to look/listen for the detection stimulus. These blocks were always the last two blocks to be performed, and the order of these two blocks was counterbalanced across participants.

Procedure

Following informed consent, participants were seated in a quiet and darkened room. Each participant completed 12 practice trials for each block type. For each block each trial began with a centrally presented fixation cross for 200 ms, followed by a blank screen for 50 ms. This was followed by the presentation of target stimulus and the detection stimulus for all blocks and the distractor stimulus for the cross–modal blocks for 500 ms. A printed response cue of 'UPorDOWN' then remained on screen until a response was made. Participants were asked to respond to the target stimulus (up or down) as quickly and as accurately as possible by pressing one of two buttons on the top surface of a PsyScope Button Box, such that the button used to respond 'up' was above the button used to respond 'down'. Once a response was recorded, a 50 ms response checking period was followed by visual feedback in the form of a centrally presented green cross (correct trials) or a red cross (incorrect trials) for 500 ms. Following feedback an additional response cue of '???' prompted participants to make a response if they perceived the detection stimulus and withhold from responding if they did not. This response cue remained on the screen until a response was made or until 1500 ms had passed (see Figure 11 for a schematic of the trial structure). They were told that the detection response was not speeded, and that they needed to wait until the '???' prompt was on the screen in order to make this response which was done by pressing the button which was on the side of a PsyScope Button Box. Upon completion of all of the experimental blocks, participants took part in the detection control blocks, in which they were instructed that they only needed to respond to the detection task, and they should focus all of their attention towards this. The entire experiment was completed in approximately 1.5 hours.

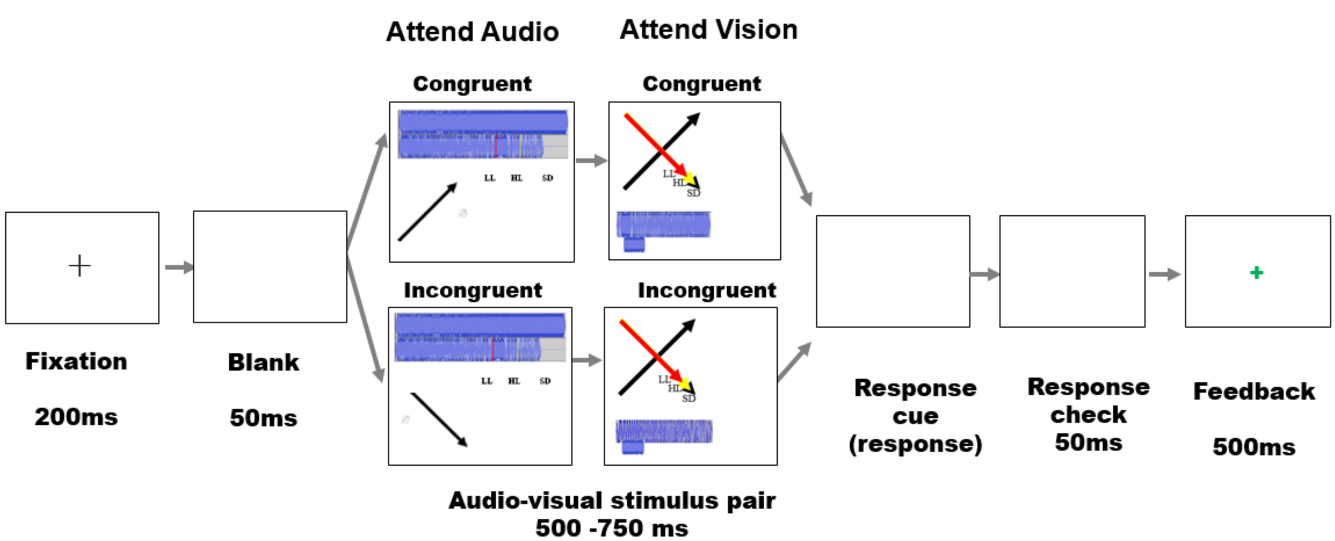


Figure 11. Trial Schematic. In both the attend–audition and the attend–vision conditions depicted above the expected response is '*UP*'. The detection stimuli were only present on half of the trials in each block and could be presented at 50 ms or 250 ms into the sound (in the case of audition), or, to the left or right of the main arrow stimulus (in the case of vision).

Results

Data from 48 participants were included in all analyses unless otherwise specified. All post hoc tests were conducted with Tukey's HSD.

Impact of difficulty on cross–modal compatibility effects

Difficulty manipulation check

To ensure that as the difficulty level increased from LL to HL to SD participants were slower and/or more errorful, a 2 (attended modality; audition, vision) x 3 (difficulty; LL, HL, SD) repeated measures ANOVA was conducted on RTs (see Figure 12a) and percent error rates (see Figure 12b) collapsed across all trial types (congruent, incongruent and neutral) in the uni–modal condition. The uni–modal condition represents a more direct measure of our manipulation check, as in these conditions there are no distractors and so any changes in processing efficiency must solely be due to the target task, which is where difficulty was manipulated.

RT data reveal a main effect of modality: F (1, 47) = 48.37, MSE = 3050000, $p < .001$, $\eta^2_p = .495$, a main effect of difficulty: F (1, 47) = 38.01, MSE = 1100000, $p < .001$, $\eta^2_p = .465$, and an interaction between attended modality and difficulty, F (1, 47) = 5.96, MSE =206000, $p < .01$, $\eta^2_p = .101$. The main effect of modality revealed that participants were slower on attend–audition (627 ms) compared to attend–vision trials (421 ms). The main effect of condition revealed that participants became slower as difficulty increased from LL (420 ms) to HL (518 ms) to SD (634 ms), and follow–up tests revealed that each difficulty level was significantly different from all the others. Finally the interaction of attended modality and condition revealed that for attend–audition, while RTs in the SD condition (740 ms) were significantly slower than RTs in both the LL (504 ms) and the HL (587 ms), conditions, the LL and HL condition were not significantly different from each other. Conversely, for attend–vision, while RTs for the LL (336 ms) condition were significantly different from both the HL (449 ms) and the SD (478 ms) conditions, these two conditions were not significantly different from each other.

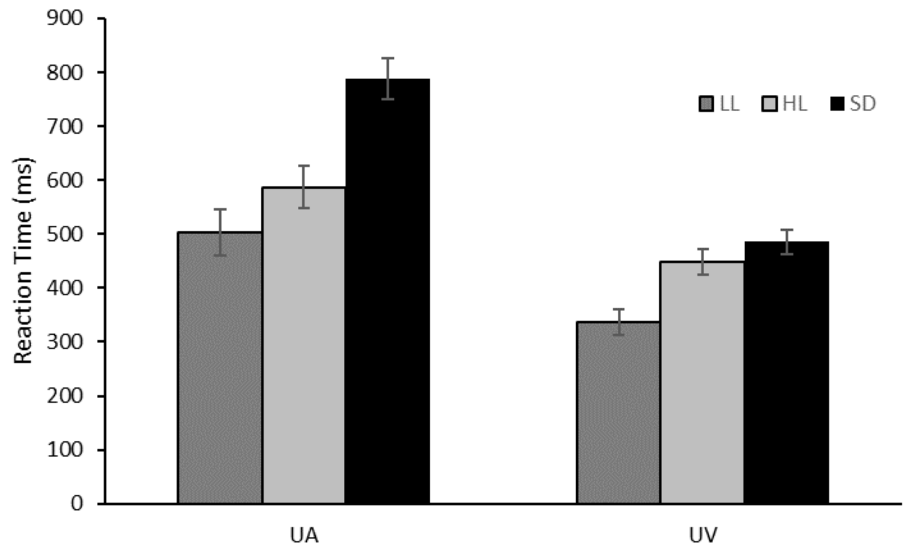


Figure 12a. Reaction times across LL, HL and SD conditions for uni–modal attend–audio (UA) and uni–modal attend–vision (UV) conditions. Error bars represent standard error.

Error rate data revealed a non–significant main effect of attended modality: *F* (1, 47) = 3.1, *MSE* = 323, $p = .085$, $\eta^2_p = .039$, but a significant effect of difficulty: *F* (1, 47) = 245.6, *MSE* = 18200, $p < .001$, $\eta^2_p = .833$, and a significant interaction between attended modality and difficulty: *F* (1,47) = 15.0, *MSE* = 1838, $p < .001$, $\eta^2_p = .234$. Similar to the RT data, the main effect of difficulty revealed that errors rates increased as the difficulty increased from LL (1.97%), to HL (12.7%) to SD (29.3%), with error rates in each condition being significantly different from all other conditions.

The interaction of attended modality and difficulty arose from the fact that attend–audition and attend–vision conditions did not differ significantly in error rates in the LL (A = 2.4%, V = 1.6%) and SD (A = 30.4%, V = 28.3%) conditions, but did in the HL condition (A = 8.1% and V = 17.3%). Importantly, post–hoc tests on this interaction revealed that, unlike the

RT data, the error rate data showed that the monotonic increase in error rates from LL to HL to SD conditions such that each level was significantly different from each other was true for both attend–audition and for attend–vision conditions.

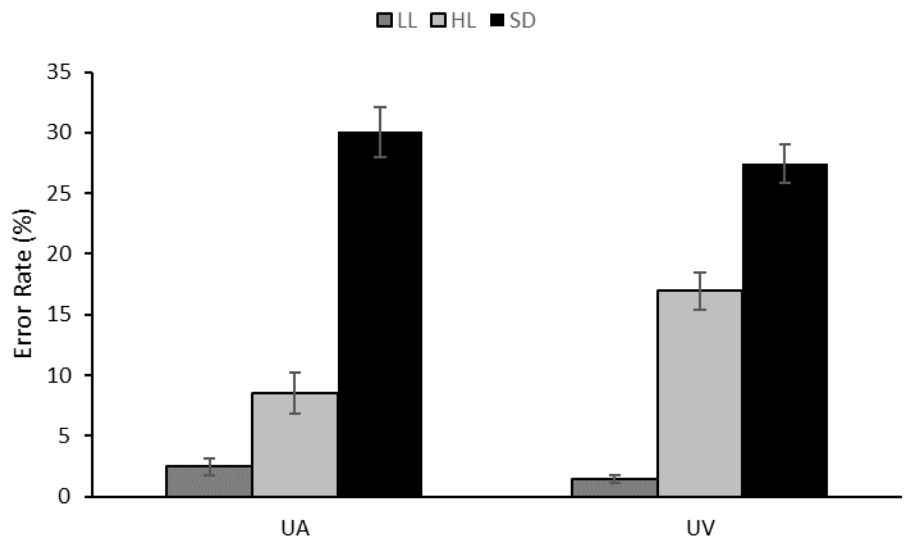


Figure 12b. Error rates across LL, HL and SD conditions for uni–modal attend–audio (UA) and uni–modal attend–vision (UV) conditions. Error bars represent standard error.

In previous reports of PL authors have also found that only RTs or error rates modulated based on difficulty (e.g., Lavie and de Fockert, 2003; Tellinghuisen &Nowak, 2003; Benoni & Tsal, 2012). In the current experiment the difficulty manipulation check revealed significant differences in error rates across the difficulty levels for each modality, which was mimicked numerically in the RT data, suggesting that our PL manipulation was successful.

Distractor effects

In the current study we were interested in determining if increasing the level of difficulty to a capacity limit (HL), and then to a data limit (SD) would have different effects on cross–modal distractor processing. To this end distractor scores were computed by subtracting performance on congruent trials from performance on incongruent trials. The distractor scores were then entered in a 2 (attended modality: audition, vision) x 3 (difficulty; LL, HL, SD) repeated measures ANOVA for both RT (see Figure 12a) and percent error rate data (see Figure 12b) for cross–modal trials only.

RT data revealed a significant main effect of modality: F (1, 47) = 10.8, MSE = 159000, p < .01, η^2_p = .200, This effect was driven by greater distraction in attend–audition (53 ms) than attend–vision (6 ms) conditions. The main effect of difficulty was non–significant (F (2, 94) = 2.3, MSE = 30100, p = .104, η^2_p = .060) as was the interaction of attended modality and difficulty (F (2, 94) = 2.50, MSE = 30200, p = .087, η^2_p = .055).

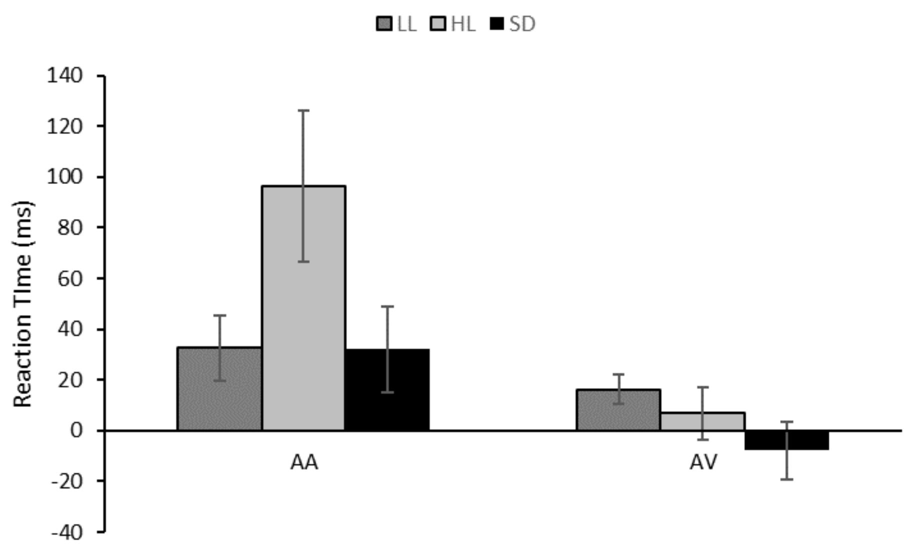


Figure 13a. Distractor reaction times. Reaction times were calculated by subtracting performance on congruent trials from performance on incongruent trials. Resultant reaction times are displayed across LL, HL and SD conditions for cross–modal attend–audio (AA) and cross–modal attend–vision (AV) conditions. Error bars represent standard error.

Error rate data revealed that the main effect of attended modality was non–significant (F (1, 47) = .108, MSE = 16.2, p = .744, η^2_p = .004). The main effect of difficulty F (2, 94) = 2.54, MSE = 219, p = .084, η^2_p = .050, and of the interaction between attended modality and difficulty F (2, 94) = 2.43, MSE = 144.7, p = .094, η^2_p = .039, were trending towards significance. The trending effect of difficulty revealed the HL condition (4.8%) to be more errorful than the LL condition (1.9%; p = .092), with neither of these differing from the SD condition (2.5%). The trending interaction of modality and difficulty revealed that the trend for increased distraction in the HL relative to the LL was driven by the attend–audio condition in which this difference was very close to significance (p = .054).

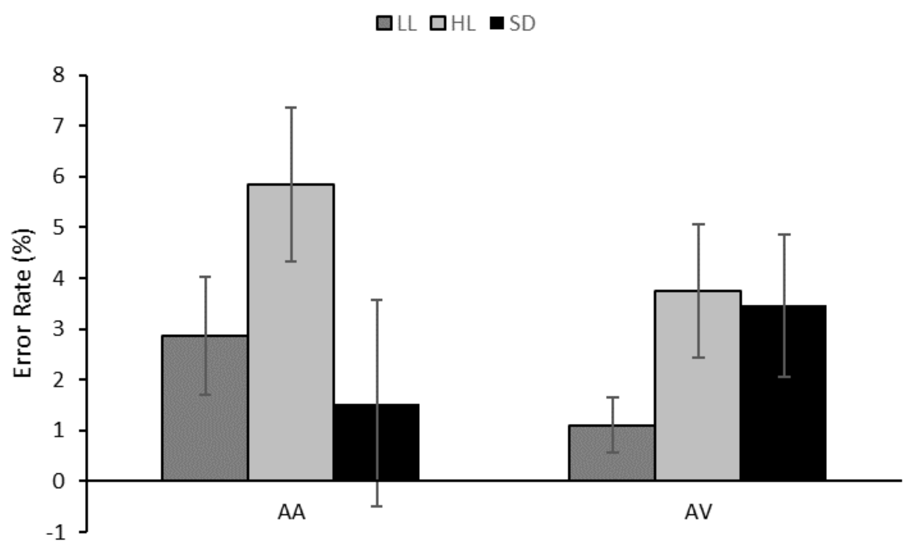


Figure 13b. Distractor error rates. Error rates were calculated by subtracting performance on congruent trials from performance on incongruent trials. Error rates are displayed across LL, HL and SD conditions for cross–modal attend–audio (AA) and cross–modal attend–vision (AV) conditions. Error bars represent standard error.

Overall the statistical trends in the data suggest that distraction by the unattended modality was not impacted by the difficulty of the task in the attended modality.

Signal Detection Theory: sensitivity (d′) response bias (β) effects.

A second main aim of the current manuscript was to determine if detection of a cross–modal[6] distractor is modulated by difficulty in the attended modality. To this end we used signal detection theory to calculate a measure of sensitivity (d′) which provided an indication of how likely participants were to detect a stimulus for each of the difficulty levels, as well as measure of response bias (β) which provided an indication of how liberal or conservative participants were in making their detection stimulus present responses. Participants with less than 75% correct detection in the control blocks (in either modality) were eliminated from the analysis. In total 14 participants were excluded, 9 based on low auditory detection rates, 3 based on low visual detection rates, and two based on low detection rates in both modalities. Of the remaining participants the average correct detection for audition was 92.4% and for vision was 97.2%. A further 9 participants were excluded due to a failure to make any correct hits or false alarms in any one of the blocks, as this suggests that participants chose not to perform the detection task in that block. Thus, d' was calculated based on 24 participants' data.

d′

d′ was calculated by subtracting the z score of the false alarm rate, from the z score of the hit rate (Green & Swets, 1966). Only trials in which the main target task response was correct were included in d′ analysis (after Raveh & Lavie, 2015). d′ values were then entered into a 2 (attended modality: auditory, visual) x 3 (difficulty: LL, HL, SD) repeated measures ANOVA. The results revealed significant main effects of attended modality|, F (1, 23) = 16.97, MSE = 15.46, $p < .001$, η^2_p = .425, difficulty, F (2,46) = 5.92, MSE = 2.95, $p < .01$, η^2_p = .205 and a

[6] Participants also took part in a uni-modal detection task, however due to concerns with the design of this task in the attend-audio condition the data from the uni-modal task are not included in the main analysis. See Appendix A for a joint analysis of the uni-modal and cross-modal detection tasks.

significant interaction between difficulty and attended modality: F (2,46) = 4.21, MSE = 1.98, $p < .05$, $\eta^2_p = .155$ (see Figure 14a)

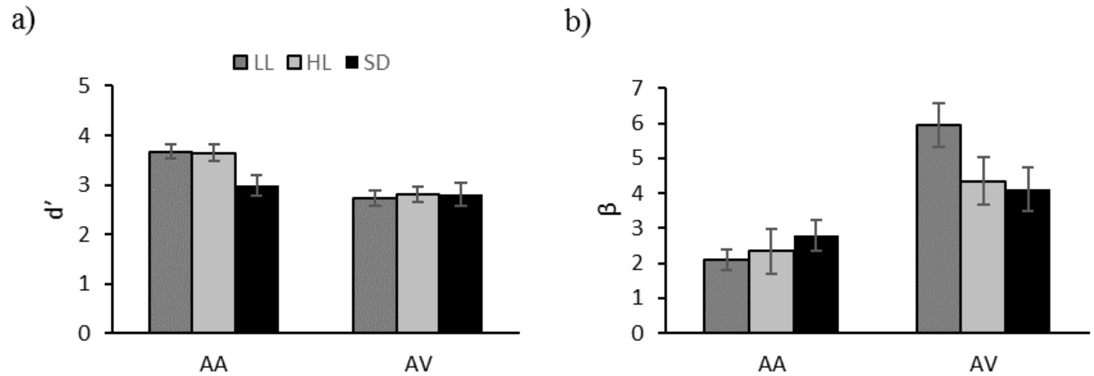


Figure 14. d′ (a) and β (b) results across LL, HL and SD conditions for cross–modal attend–audio (AA) and cross–modal attend–vision (AV). Error bars represent standard error.

The main effect of attended modality revealed that participants were more sensitive to the detection stimuli when they were attending to vision (3.05) compared to audition (2.9). Regarding the main effect of difficulty, follow up tests indicated that while sensitivity remained stable across LL (3.20) and HL (3.22) conditions, it decreased significant from both of these conditions to the SD condition (2.89). Finally, follow up tests on the interaction between difficulty and attended modality revealed that the sensitivity decrease in the main effect of difficulty was again driven by the attend–audio condition, as there was significantly less sensitivity in the attend–audio SD (2.98) than HL (3.64) or LL (3.67) conditions. In contrast there were no significant difference between any of the difficulty levels (LL = 2.74, HL = 2.80, SD = 2.80) in the attend–vision condition.

Overall these data suggest sensitivity was greater for attend–vision conditions compared to attend–audition conditions. Importantly, the data reveal that sensitivity decreased at the highest level of difficulty (SD) compared to either of the other conditions (LL, and HL) during attend–audition only.

β

β was calculated by multiplying d′ by –.5 multiplied by the addition of the z scores of the hit and false alarm rates (Green & Swets, 1966). Again, only trials in which the main target task response was correct were included in β analysis (after Raveh & Lavie, 2015). Resultant data were then entered into a 2 (attended modality: auditory, visual) x 3 (difficulty: LL, HL, SD) repeated measures ANOVA. A significant main effect of attended modality: F (1, 23) = 21.96, MSE = 197.3, $p < .001$, $\eta^2_p = .488$, emerged, as did a significant interaction between difficulty and attended modality: F (2, 46) = 6.55, MSE = 19.9, $p < .01$, $\eta^2_p = .222$. The main effect of difficulty was non–significant: F (2, 46) = .62, MSE = 4.3, $p = .54$, $\eta^2_p = .026$ (see Figure 14b). The main effect of attended modality revealed that participants used a more conservative criterion in attend–vision (A = 2.43, V = 4.77) conditions. The interaction of difficulty and attended modality revealed the attend–vision LL condition had a significantly more conservative criterion than all auditory conditions and than the visual SD condition with a near significant difference ($p = .068$) with the visual HL condition.

Overall the response bias data suggest that criterion was stable across the conditions, with the exception of the attend–vision LL condition, which had the most conservative criterion.

Discussion

The current study had 3 main findings. The first was that a single manipulation was successfully used to promote capacity and data limited processing. Second, there was little evidence of changes in distraction from LL to either HL or SD conditions, with overall trends for increased distraction under HL and SD conditions, supporting a view of independent resources across modalities. Third, no reliable support for a dissociation of data and capacity limits on cross–modal distractor processing was found, and this was supported by both the compatibility and the detection analysis.

There has been little research focused on directly comparing the effects of capacity and data limited processing on distractor effects. The few studies which have directly compared the two, have done so using different manipulations to achieve capacity and data limited processing (e.g., Lavie & de Fockert, 2003; Benoni & Tsal, 2012). Furthermore, some studies that intended to look at the effects of capacity limits have done so using typical manipulations of the quality of data (e.g., Handy, Soltani & Mangun, 2001; Handy & Mangun, 2000) and in these instances have found effects in line with capacity limitations. As suggested by Yeshurun and Marciano (2013), while typical manipulations of SD (promoting data limited processing) involve reducing the salience of the target, this is not an effect that is seen in typical PL manipulations (promoting capacity limited processing) and thus distractor processing may be promoted under data limited designs but under not capacity limited designs. Given that data and capacity limits exist on a continuum (Norman & Bobrow, 1975), one potential method to dissociate the two is not based on the manipulation itself, but based on participants' performance. True data limited processing should result in high error rates, while capacity limited processing should not led to such an increase in error rates (Madden & Langley, 2003). In the current study, error rates in the HL condition were 12% which is similar to those reported in previous literature (thesis Experiment 1 HL = 7%; Lavie and de Fockert, HL = 9%; Maylor & Lavie[7], HL = 7%). The error rates in the SD condition in the current study were 26%, which are higher than those typically reported for PL manipulations and are in line with the suggestion that data limited processing is observed

[7] This is for the younger group only which is comparable to the current study

when error rates increase towards 20% to 25% (Madden and Langley, 2003). Thus, in the current study, we used a single manipulation to achieve data and capacity limited processing which will render any comparisons between these conditions free of additional confounds created by the use of different manipulations to achieve these two types of processing.

The compatibility and detection analysis both failed to find any significant differences in distractor processing across LL and HL conditions. This was true for both attend–audio and attend–vision conditions. There was however a trending main effect of difficulty in the compatibility data which was subsumed by a trending modality by difficulty interaction. Numerically the data revealed during attend–vision conditions, there was an increase in distractor processing from LL (1.1%) to HL (3.7%), with this same pattern in attend–audition approaching significance (p = .054; LL = 2.8%, HL = 5.8%). Under conditions of independent processing resources for each modality, it is not expected to find the typical uni–modal pattern of decreased distractor processing under HL conditions, since regardless of the amount of resources employed for target processing in one modality, the same amount of processing resources would remain in the distractor modality. While there remains much conflict in the literature regarding whether resources are controlled at a supramodal or a modality level, the current results are in line with previous studies showing no impact (current statistical trends in compatibility and detection data) or increased distraction (current numeric trends in compatibility) during cross–modal HL relative to LL conditions (Sandhu & Dyson, in press; Vroomen, et al., 2002; Tellinghuisen & Nowak, 2003; Jacoby et al., 2013). Importantly, a failure to modulate distractor processing by PL, or an increase in distraction under HL conditions, both support the view that capacity limits arise at the modality level.

In comparing distractor processing between the LL and SD conditions in the compatibility data, no significant differences were found, however there was a trending interaction of modality and difficulty. Numerically, in vision there was an increase in distraction from LL (1.1%) to SD (3.6%), however, in attend–audition there was a decrease in distraction from LL (2.8%) to SD (1.3%). Similarly, in the detection data a significant decrease in sensitivity for the distractor was observed in the SD (2.89) relative to LL (3.20) condition during attend–audition, and this effect could not be accounted for by participants placing less weight on the detection task in the attend–audition SD condition, as response bias did not change across any of the attend–audition conditions. This result is somewhat surprising, as regardless of whether resources are shared or independent across modalities we may have expected to find an increase in distractor processing under conditions of SD, in line with previous work (thesis Experiment 2; Yuval–Greenberg & Douelle, 2009). This is because there is evidence in the cross–modal domain which demonstrates that when one modality is degraded, there is a widening of attentional scope such that sensory weighting is shifted in favour of the intact modality (Ernst & Banks, 2002). In the current study the intact modality is the distractor, and thus we would expect increased distraction during degraded conditions. One potential explanation for this finding is related to the design of the current study. For attend–audio conditions participants were asked to determine which sound was longer, the one that was going ‘up’ or the one that was going ‘down’. In the LL condition the auditory response can be selected at 400 ms or 450 ms, in the HL at 500 ms or 550 ms, and in the SD condition at 600 ms or 650 ms (see Figure 1). Importantly, the duration of the visual distractor image was 525 ms. Thus, the SD condition is the only one in which there is a significant gap (either 75 ms or 125 ms) between the offset of the visual image and the earliest possible resolution of the auditory stimulus. Given that audio–visual integration is promoted by close temporal proximity (e.g., Chen & Spence, 2010), it may be the case that in the SD condition the visual processing would have had to be completed prior to resolving the auditory stimulus and so integration of the auditory and visual stimulus were not promoted, leading to the observed reduction in distractor effects in this condition. This design choice was made to keep the attend–audio and attend–vision conditions as similar as possible and in attend–vision conditions the visual stimulus was displayed for 500 ms. Presenting the visual stimulus for a longer duration in the attend–vision condition was not desirable, as this may have made the task too easy (previous research using a similar manipulation used a 150 ms target presentation rate; Macdonald & Lavie, 2011).

Taken together, in addition to supporting the view that resources are independent across modalities, the data from the current study does not provide evidence in favour of a dissociation between data and capacity limited condition on cross–modal distractor processing. While there may be some concerns regarding the attend–audio–degraded condition showing a trend (compatibility data) or a significant (detection data) pattern of decreased distraction in the SD condition, this is likely due to the specific design of this condition, as discussed above. The remaining data show trends of increased distraction in HL and SD conditions, however none of these effect were significant. As discussed, the finding of a null effect in the capacity limited condition is not surprising under independent resources, however this finding in the data limited condition was unexpected. As discussed, an increase in distraction in degraded conditions was expected based on principles of multisensory integration (inverse effectiveness; Stein & Meredith, 1993) and based on previous studies which have demonstrated increased distraction under degraded conditions during selective attention tasks (e.g., thesis Experiment 2; Collignon et al., 2008; Yuval–Greenberg & Douelle, 2009). One difference between these studies and the current study is that these previous studies used naturalistic object stimuli, and there is evidence to suggest that doing so promotes cross–modal integration (Chen & Spence, 2010). While there is a semantic relationship between the stimuli in our task, it may not have been strong enough to promote integration.

The lack of significant increases in distraction in the current study, despite such effects being reported in previous cross–modal investigation of both HL (e.g., Jacoby, Hall & Mattingley, 2012; Tellinghuisen & Nowak, 2003) and SD (Yuval–Greenberg & Douelle, 2009) conditions, may provide further support for independent processing resources across modalities, as it suggests that distractor processing is only modulated when the audio and visual components of the stimuli are integrated. In the study by Lavie and de Fockert (2003), a typical flanker task was used in the degraded condition such that the target letter was centrally presented with reduced contrast and size relative to a peripherally presented distractor letter. Under these conditions, the authors found increased distraction relative to a LL condition in which the target letter was presented at full size and contrast. Given the spatial disparity between the target and distractor letters in the display, it is unlikely that these would be integrated, however increased distraction occurred. Thus, the apparently stricter requirement of integration in order for increased distractor effects to appear in cross–modal contexts suggests a flexibility such that resources for distractor processing are only recruited when beneficial. Specifically the widening of attentional scope to include distractors is most likely to occur when the target and distractor are thought to arise from a common source, which in real life situations would typically be beneficial as a single object (image of a lion or sound of a lion) should led to the same behavioural response (run!).

The important role of integration with respect to distractor processing in the cross–modal domain is supported by the weaker distractor modulation found in the current study (thesis Experiment 3) in which the use of naturalistic stimuli were not used to promote integration and the stronger distractor modulation effects found in previous studies, in which this factor was employed (thesis Experiment 2; Yuval–Greenberg & Douelle, 2009). In addition, there is also support for the role of integration within the current study via a comparison of the attend–audio SD condition with all other conditions. The audio SD condition was the one in which integration was promoted the least due to having the largest temporal gap between the offset of the visual stimulus and the earliest possible resolution of the auditory stimulus. This condition was also the only one to show a numeric or significant decrease in distraction relative to the LL conditions, providing further support for a role of integration in audio–visual distractor processing. Furthermore this finding suggests that the role of integration is a greater driver of the success of selective attention than SD, as the signal was reliably degraded in the attend–audition SD condition based on the manipulation check, but this did not result in the expected increase in distractor processing. This hypothesis can be further substantiated in future research which includes two SD conditions, one in which integration is promoted and another in which it is not.

Finally, in the current study both the compatibility and the detection data revealed similar patterns of results. This is important as some theories of attention suggest that all information is processed at the perceptual level, but not at the semantic level (e.g., Broadbent, 1958; Treisman, 1960). When inferring independence across processing resources across modalities it is critical to ensure that any null effects found in the compatibility data are not just an artefact of distractors not being processed at the semantic level which would be required in order for compatibility effects to be revealed. In the current study we were able to rule out this possibility as the detection data showed similar patterns to the compatibility data, specifically no impact of difficulty on distraction (excluding the attend–audition SD condition; although in this condition similar patterns were also seen in both compatibility and detection data).

In conclusion, the current study does not support a dissociation between data and capacity limits on cross–modal distractor processing, as neither data nor capacity limited conditions impacted distractor processing relative to LL conditions. That there was no modulation of distractor processing based on the difficulty level of the task provides strong support for independent processing resources across modalities, and this effect was seen in both the compatibility and the detection data.

Chapter 5: Cross experiment analyses

Cross experiment analyses

The main aim of the current dissertation was to assess the impact of PL and SD on cross–modal selective attention. Given that all three experiments in the current dissertation were assessing the impact of similar factors on cross–modal selective attention, and that all included compatibility (distractor) effects as one of the dependent variables, cross–experiment analysis were carried out to further substantiate the results from the individual studies. The rationale and results of the Cross–Experiment analyses are presented below. The results of all cross–experiment analyses will be discussed in the General Discussions (Chapter 6)

Impact of PL: Experiments 1 and 3 combined analysis

In both Experiments 1 and 3, there were numerical trends for increased distraction in the HL relative to the LL condition. As such, in order to determine if more conclusive statements could be made regarding the impact of increased PL on cross–modal distractor processing a combined analysis of the LL and HL conditions of Experiments 1 and 3 was carried out. In addition to determining if the increased power of the combined analysis would led to significant effects, this analysis allowed us to determine whether there were any differences in overall patterns between the two experiments. Specifically, overall distractor effects were weak in Experiment 3, particularly in the finding of no trend for increased distraction in the SD relative to LL condition, as this is a fairly consistent finding in the literature (e.g., Yuval–Greenberg & Douelle, 2009; Collignon et al., 2008). One potential explanation for this, as discussed in Chapter 4, is that previous investigations employed naturalistic stimuli which also aid in promoting cross–modal integration which increases distractor processing (Chen & Spence, 2010). The combined analysis of distractor effects in Experiments 1 and 3, (and Experiments 2 and 3 discussed in turn below), can also offer insights into the impact of naturalistic stimuli as these were employed in Experiments 1 (and 2), but not in Experiment 3. Thus, findings of a main effect of Experiment, with greater distraction in Experiments 1 (and 2) relative to Experiment 3 can strengthen the theoretical position that the weaker distractor effects in Experiment 3 relative to previous reports were due to type of stimuli employed across studies.

Distractor scores from the 48 participants in Experiment 1, and from the LL and HL conditions from the 48 participants from Experiment 3 were combined for the following analysis of the impact of PL on cross–modal selective attention.

In both Experiments 1 and 3 distractor scores were calculated by subtracting performance on congruent trials from incongruent trials in both the RT and the error rate data. These scores were entered into a 2 (experiment; 1, 3) x 2 (attended modality; audition, vision) x 2 (PL; LL, HL) mixed ANOVA, with experiment manipulated between participants and attended modality and PL manipulated within participants.

The RT data revealed a significant main effect of experiment, F (1,94) = 28.9, MSE = 614000, $p < .001$, $\eta^2_p = .235$, a main effect of modality, F (1,94) = 10.63, MSE = 2160000, $p < .01$, $\eta^2_p = .102$ a trending main effect of PL, F (1,94) = 3.41, MSE = 536000, $p = .068$, $\eta^2_p = .035$, and a trending interaction between modality and PL, F (1,94) = 3.26, MSE = 36600, $p = .074$, $\eta^2_p = .034$ (see Figure 15a).

The main effect of experiment revealed that there were greater distractor effects in Experiment 1 (117 ms) than in Experiment 3 (37 ms). The main effect of modality revealed that there were greater distractor effects for auditory (100 ms) than for visual (53 ms) targets. Finally, the trend for PL revealed numerically greater distractor effects in HL (88 ms) compared to LL (65 ms) conditions, and the interaction between modality and load revealed that while there was significantly greater distraction in attend–audio HL compared to LL conditions, this effect was not significant for attend–vision conditions. None of the remaining interactions were significant in the RT data (all *ps* > .183, all $\eta^2_p < .034$).

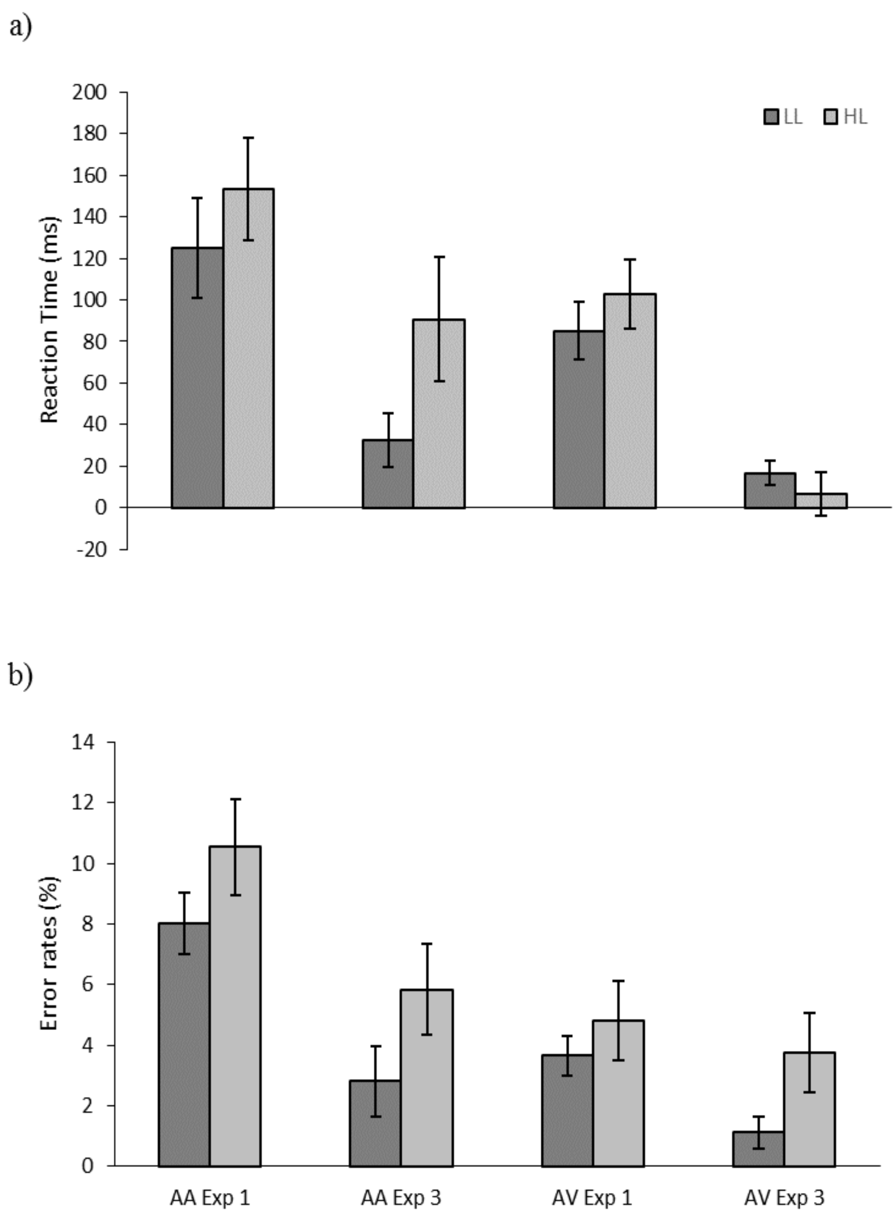


Figure 15. Distractor scores for a) reaction time and b) error rates . Distractor scores were computed by subtracting performance on congruent trials from performance on incongruent

trials, are displayed for attend–audio conditions (AA) and attend viusal (AV) conditions for LL and HL conditions in Experiments 1 and 3. Error bars represent standard error.

The error rate data mirrored the RT data in that there was a significant main effect of experiment, F (1,94) = 13.02, MSE = 1094, $p < .001$, $\eta^2_p = .122$, with greater distraction in Experiment 1 (6.7%) than Experiment 3 (3.4%). The main effect of modality was also significant, F (1,95) = 11.93, MSE = 1154 $p < .01$, $\eta^2_p = .133$, again with greater distraction in attend–audition (6.8%) compared to attend–vision (3.3%) conditions. Finally, in contrast to the RTs where there was only a trend for a main effect of load, this was significant in the error rate data, F (1,95) = 11.22, MSE = 525, $p < .01$, $\eta^2_p = .107$, with greater distraction in the HL (6.2%) compared to the LL (3.9%) conditions. Again none of the interactions were significant (all ps > .119, all η^2_ps < .026).

The cross experiment analysis on the impact of PL on distractor processing mimicked the results of each individual study in terms of showing greater distraction for audition compared to vision (although this main effect was not found in the error rate data for Experiment 3). Furthermore, in the individual analysis, both experiments showed a trend for increased distraction in HL compared to LL conditions. In the combined analysis, this trend was also found in the RT data, and was significant in the error rate data. In addition, the finding of a main effect of Experiment in both the RT and error rate data supports the suggestion in Experiment 3 that the relative weak distractor effects may have been the result of the stimuli used.

Impact of SD: Experiments 2 and 3 combined analysis

In Experiment 2, significant increases in distractor processing in the SD relative to the LL condition were observed, however, such differences were not observed for Experiment 3. As such, a combined analysis of the LL and SD conditions in Experiments 2 and 3 were conducted in an attempt to strengthen conclusions regarding the impact of SD on cross–modal distractor processing. Furthermore, as discussed above, the impact of the type of stimuli used was further assessed by a comparison of overall distractor effects in Experiment 2 (naturalistic stimuli) relative to Experiment 3 (abstract stimuli).

Overall distractor scores from 48 participants in Experiment 2, and the distractor scores from the LL and SD conditions from the 48 participants from Experiment 3 were combined for the following analysis of the impact of SD on cross–modal selective attention.

In both Experiments 2 and 3 distractor scores were calculated by subtracting performance on congruent trials from performance on incongruent trials. These scores were entered into a 2 (Experiment; 2, 3) x 2 (attended modality; audition, vision) x 2 (SD; LL, SD: see Figure 16) mixed ANOVA, with experiment manipulated between participants and attended modality and SD manipulated within participants. The RT data revealed a significant main effect of experiment F (1,94) = 65.61, *MSE* = 692000, $p < .001$, $\eta^2_p =$ .411, a main effect of modality F (1,94) = 30.70, *MSE* = 346000, $p < .001$, $\eta^2_p = .246$, and an interaction of experiment by attended modality, F (1,94) = 7.71, *MSE* = 86900, $p < .01$, $\eta^2_p = .076$ (all other ps > .205, all η^2_ps <). The main effect of experiment revealed that there were greater distraction effects in Experiment 2 (104 ms) than in Experiment 3 (19 ms). The main effect of modality revealed that there were greater distractor effects for auditory (92 ms) than visual (32 ms) targets. Finally the interaction of experiment and modality revealed that audition had significantly more distraction in Experiment 2 (149 ms) than 3 (59 ms), however vision did not see any significant differences across Experiments 2 (34 ms) and 3 (4 ms).

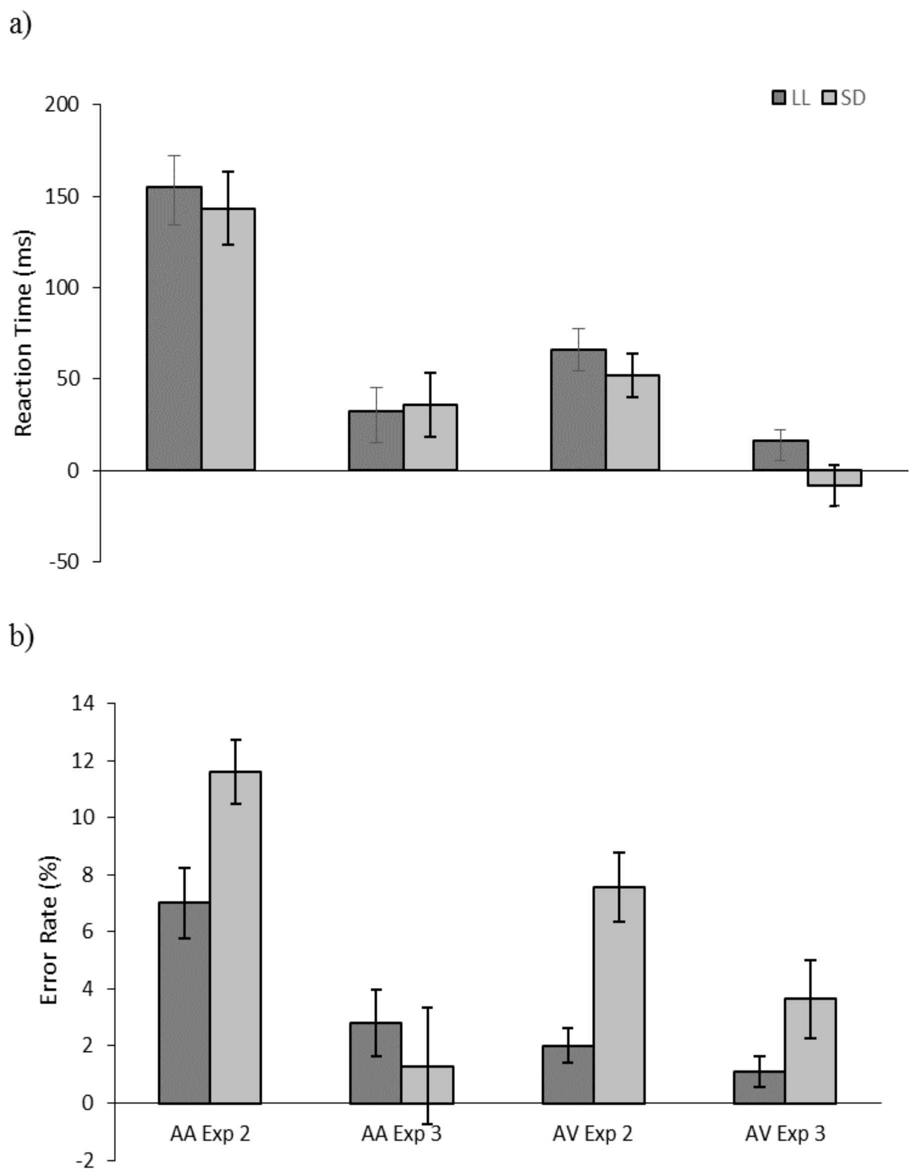


Figure 16. Distractor scores for a) reaction time and b) error rate data. Distractor scores which were computed by subtracting performance on congruent trials from performance on incongruent trials, are displayed for attend–audio conditions (AA) and attend–vision (AV) conditions for the LL and SD conditions in Experiments 2 and 3. Error bars represent standard error.

The error rate data revealed significant main effects of experiment: F (1,94) = 23.49, MSE = 2246, p < .001, η^2_p = .200, a main effect of modality: F (1,94) = 5.71, MSE = 420, p < .05, η^2_p = .057, and a main effect of degradation: F (1,94) = 10.12, MSE = 749, p < .01, η^2_p =.097. These main effects were due to greater distraction in Experiment 2 (7.0%) compared to

Experiment 3 (2.2%), in attend–audition (5.7%) compared to attend–vision (3.6%) conditions, and, in degraded (6.0%) compared to intact (3.2%) conditions.

These main effects were subsumed by significant interactions between modality and experiment: F (1,94) = 7.65, MSE = 563, p < .01, η^2_p = .075, and between degradation and experiment: F (1,94) = 6.72, MSE = 497, p < .05, η^2_p = .067, in addition to a trending interaction between modality and degradation: F (1,94) = 2.93, MSE = 151, p = .09, η^2_p = .030 (the interaction between modality, degradation and experiment was non-significant p = .297, η^2_p = .012). The interaction of modality and experiment arose due to the fact that audition experienced significantly greater distraction in Experiment 2 (9.3%) compared to Experiment 3 (2.0%), while there was no significant differences across experiments for vision (Experiment 2 = 4.8%, Experiment 3 = 2.4%). Furthermore, the difference between distraction based on attended modality was significant in Experiment 2, with audition experiencing more distraction than vision, but this was not significant in Experiment 3. The interaction of experiment and degradation revealed that participants only had greater distraction during degraded (9.6%) relative to intact (4.5%) condition in Experiment 2, whereas distraction was not significantly different across intact (2.0%) and degraded (2.5%) conditions in Experiment 3. Finally, the trending interaction between modality and degradation arose due to significantly greater distraction in SD relative to LL in attend–vision (LL = 1.6%, SD = 5.6%) but not attend–audition conditions (LL = 4.9%, SD = 6.4%).

Findings of greater overall distraction in Experiment 2 versus 3, provide support for the notion that weaker effects of distraction in Experiment 3 compared to previous reports (Yuval–Greenberg & Douelle, 2009; Collignon et al., 2008) were due to the use of naturalistic stimuli in these studies and Experiment 2, but not the current Experiment 3. The experiment and modality interaction in both the RT and error rate data showed that while audition had significantly more distraction in Experiment 2 compared to Experiment 3, this effect was not significant for vision. Furthermore, audition only received more distraction than vision in Experiment 2, but not Experiment 3. These effects can be interpreted within a framework of visual dominance for object recognition, as given that vision is the dominant modality for object recognition, it would be expected that the effects of visual distractors would be greater overall in Experiment 2 compared with Experiment 3. Furthermore, visual dominance also explains why audition had more distraction than vision in Experiment 2, but not in Experiment 3.

The experiment by degradation interaction revealed that, in line with the individual analyses of Experiments 2 and 3, that the main effect of degradation was only significant in Experiment 2 but not in Experiment 3. The trending interaction of modality and degradation suggested that while vision saw significantly greater distraction in degraded compared to intact trials, this was not true for audition. Again, this interaction may in part be due to the confound in the attend–audio SD condition in Experiment 3 (see Chapter 4), which led to no modulation of distractor effects in attend–audio conditions. Given this potential, follow–up tests on the non–significant three–way interaction of modality, degradation and condition were conducted, as this effect is critical in determining if the modality by degradation effect is driven by Experiment 3. Post hoc tests on this interaction show that while there are indeed significant increases in distraction in both attend–audio and attend–vision conditions in Experiment 2, this is not true in Experiment 3. The interaction of modality and degradation is likely driven by non–significant, but increased distraction in visual degraded conditions in Experiment 3, while audition shows a trend for decreased distraction in the attend–audio condition. Thus, when combined, overall the effect of degradation is significant for vision, but not audition.

Comparison of PL and SD effects: Experiments 1 and 2 cross–analysis

Experiment 3 aimed to directly contrast the impact of HL and SD on distractor processing. The data revealed that neither the HL nor the SD conditions were significantly different from the LL conditions, suggesting that data and capacity limits have the same impact on cross–modal selective attention. However, in this study the overall distractor effects were weaker compared to previous reports (Yuval–Greenberg & Douelle, 2009) and a novel, continuous manipulation was used in order to promote both HL and SD conditions. Furthermore, while there was a general trend for increased distraction in HL and SD, this was not true of the attend–audio SD condition. Thus we sought to replicate the finding of Experiment 3 in a cross analysis of Experiments 1 and 2. Findings of no difference in distraction in the HL and SD conditions of this experiment would strengthen the conclusion that data and capacity limited conditions both have the same impact on cross–modal selective attention.

Given that Experiment 3 only had distractor scores, as no neutral trials were presented in this experiment, only distractor scores from Experiment 1 and 2 are included in the following analysis, as this analysis is aimed at strengthening the conclusion made in Experiment 3. Distractor scores from 48 participants in the HL condition in Experiment 1, and distractor scores from 48 participants in the SD condition from Experiment 2 were included in the following analysis. Distractor scores were computed by subtracting performance on congruent trials from performance on incongruent trials. Distractor scores were then entered into a 2 (modality: audition (A), vision (V)) x 2 (condition; HL (Experiment 2), SD (Experiment 3) mixed ANOVA, with modality as a within participants factor and condition as a between participants factor, for both RT and error rate data (see Figure 17).

RT data revealed only a significant main effect of modality; *F* (1,94) = 13.54, *MSE* = 241000, $p < .001$, η^2_p = .126, which revealed that greater distractor effects were in evidence for attend–audition (148 ms) compared to attend–vision (77 ms) conditions. Critically, the main effect of condition was not significant; *F* (1,94) = 2.71, *MSE* = 443000, $p = .103$, η^2_p = .028. This non–significant effect showed that there was no difference in distraction between the HL condition of Experiment 1 (128 ms) and the SD condition of Experiment 2 (98 ms). Finally the interaction between modality and condition was non–significant; *F* (1,94) = 1.15, *MSE* = 20600, $p = .285$, η^2_p = .012.

The error rate data revealed the same effects as the RT data. Specifically, there was a main effect on modality: *F* (1,94) = 14.05, *MSE* = 1143, $p < .001$, η^2_p = .130, which again revealed greater distraction in attend–audition (11.1%) compared to attend–vision (6.2 %) conditions. Once again, the critical main effect of condition was non–significant: *F* (1,94) = 2.09, *MSE* = 176, $p = .152$, η^2_p = .022, which suggests equivalent distraction in the HL condition of Experiment 1 (7.7%) and the SD condition of Experiment 2 (9.6%). There was no significant interaction between attended modality and condition: *F* (1,94) = .427, *MSE* = 35, $p = .515$, η^2_p = .005. Overall the results of this analysis provide support for the general pattern of equivalent distraction observed in the HL and SD conditions of Experiment 3, supporting the conclusion that data and capacity limits have the same impact on distractor processing.

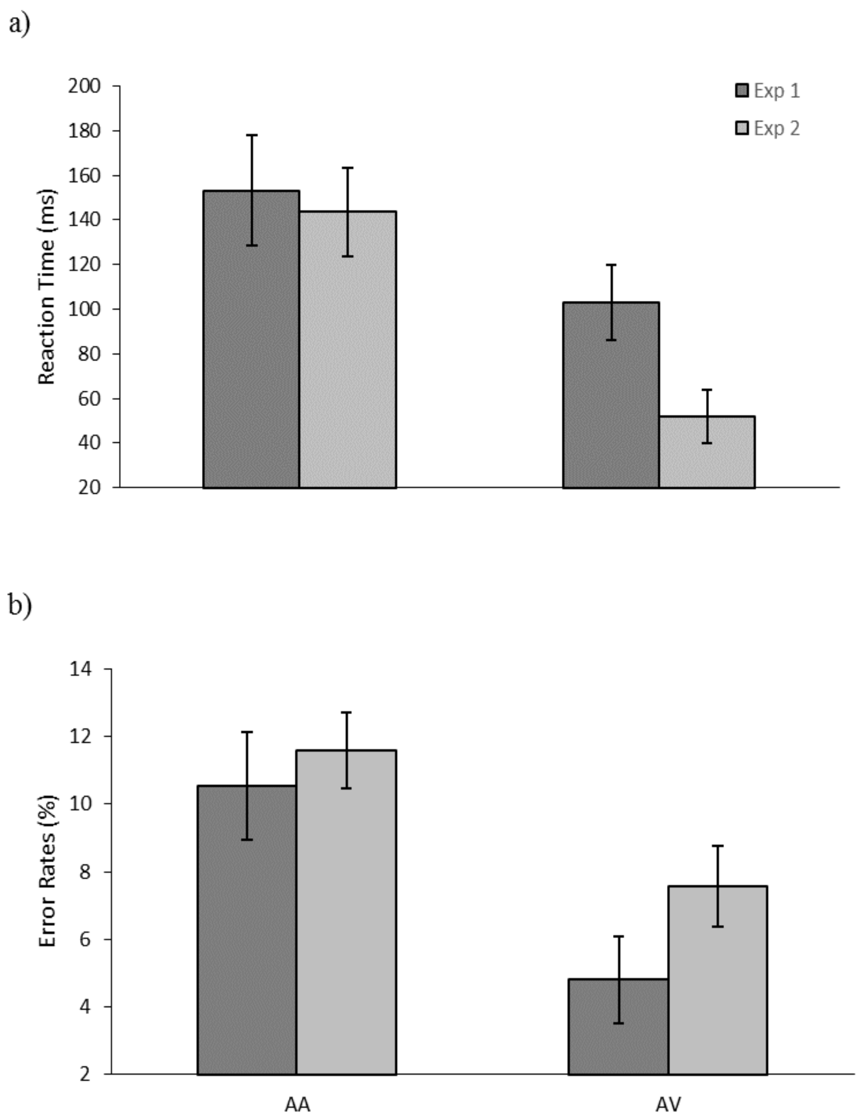


Figure 17. Distractor scores for a) reaction time and b) error rates. Distractor scores which were computed by subtracting performance on congruent trials from performance on incongruent trials, are displayed for attend–audio conditions (AA) and attend–vision condition (AV) in Experiment 1 (HL condition) and 2 (SD condition). Error bars represent standard error.

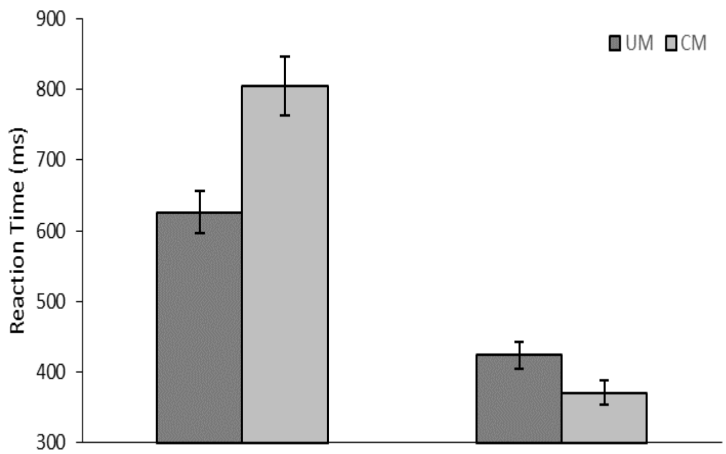
Comparison of uni–modal and cross–modal performance in Experiment 3.

Finally, in Experiment 2, differences between facilitation and interference effects were observed, based on the attended modality. As discussed in Chapter 3, this may have been due to the use of a bi–modal baseline condition, as previous work suggests that the presence of an auditory stimulus improves visual processing efficiency over uni–modal conditions, while the presence of a visual stimulus decreases auditory processing efficiency over uni–modal conditions. In Experiment 2, there was not a uni–modal condition in which to verify that this may have contributed to resultant data patterns. However, in Experiment 3, there were both uni–modal and cross–modal conditions, and thus in order to provide empirical support within the current dissertation for a differential pattern of facilitation and interference in uni– versus cross–modal auditory and visual selective attention, the uni–modal and cross–modal conditions in Experiment 3 were compared.

Performance from 48 participants in Experiment 3 were entered into a 2 (task; uni–modal, cross–modal) by 2 (modality: attend–audio, attend–vision) ANOVA for both RT and error rate data (see Figure 18). Performance across the different difficulty levels were collapsed, as the interest in this analysis rests in examining whether patterns of facilitation and interference across uni–modal and cross–modal selective attention differed based on attended modality.

The RT analysis revealed a main effect of task; F (1,47) = .15.4, MSE = 189 000, p < .001, η^2_p = .247, a main effect of modality; F (1,47) = 139.9, MSE =487 000, p < .001, η^2_p =.748 and an interaction between task and modality; F (1,47) = 46.9, MSE = 644 000, p < .001, η^2_p = .500. The main effect of task revealed slower processing for cross–modal (588 ms) than for uni–modal (525 ms) conditions and the main effect of modality revealed slower processing for attend–audio (716 ms) compared with attend–vision (397 ms) conditions. Importantly, follow up tests on the interaction between task and modality revealed that for attend–audition, uni–modal (626 ms) processing was faster than cross–modal (805 ms) processing. However, for attend–vision conditions, uni–modal processing (424 ms) was slower than cross–modal processing (371 ms). Furthermore there were no significant difference between uni–modal attend–audition conditions and cross–modal attend–vision conditions. The Error rate data revealed no significant effects (all ps > .158, all η^2_ps < .042). The current analysis provides some support for vision benefiting from cross–modal compared to uni–modal processing, while cross–modal processing is worse than uni–modal processing for audition.

a)



b)

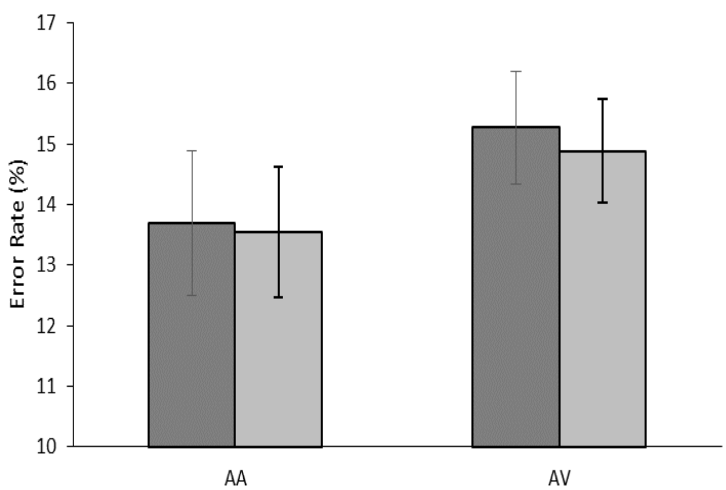


Figure 18. Overall processing efficiency for attend–audio (AA) and attend–vision (AV) conditions for uni–modal (UM) and cross–modal (CM) conditions, collapsed across difficulty for a) reaction time and b) error rate data . Error bars represent standard error.

Chapter 6: General Discussion

The present dissertation examined the influence of capacity and data limits on cross–modal distractor processing. Specifically, I was interested in the impact of PL (thought to represent a capacity limit) and SD (thought to represent a data limit). I was additionally interested in how other factors such as the assignment of modality to target or distractor (attend–vision–ignore auditory, attend–audition–ignore visual), the nature of the stimuli used (naturalistic or abstract) and individual differences in attentional control would interact with PL and SD in their influence on distractor processing. The results from the current experimental series led to four main conclusion regarding cross–modal selective attention. First, the observation of increased distraction during HL relative to LL conditions (trending in Experiments 1 and 3, significant in the combined analysis of Experiments 1 and 3) rather than the typically observed decrease that is reported in the uni–modal literature, supports the view that attentional resources are modality specific (e.g., Treisman and Davies, 1973; Wickens, 1980; Wickens, 1984; Duncan, Martens and Ward, 1997). Second, the evidence showing increased distractor processing during data limited (significant in Experiment 2, trending in the attend–vision condition of Experiment 3, significant in the attend–vision condition for the combined analyses of Experiments 2 and 3) conditions suggests that there are similarities between data and capacity limited processing in the cross–modal domain. As discussed in Chapter 4, the lack of significant (or trending) increases in distraction during attend–audition during Experiment 3 is likely due to the specific design of that condition, in which distractor integration was not promoted due to a large temporal gap between the resolution of the target and distractor information. Third, the results suggest a role of attended modality in cross–modal distractor processing (Jacoby et al., 2013) in that across all three studies audition received greater distraction from vision than vice versa. A processing efficiency (e.g., Mordkoff & Yantis, 1991) account, where vision was processed more efficiently than audition and thus had a stronger distracting impact on audition, could only partially explain the data. There was evidence that additional factors such as the nature of the stimuli also played a role (Welch & Warren, 1980), as this modality asymmetry was larger in Experiments 1 and 2 (using naturalistic stimuli) compared with Experiment 3 (using more abstracted stimuli). Finally, the lack of correlations between uni–modal and cross–modal selective attention tasks further support different mechanisms for uni–modal and cross–modal selective attention processes. These finding will be discussed in turn below.

Independent processing resources across modalities

In the current dissertation distractor scores were used as a measure of the independent or shared nature of resources across modalities. Given that PL is thought to exhaust resources in the target modality, effects of distraction by a secondary modality should only decrease if that secondary modality shares resources with the target modality. In Experiment 1 the expected decrease in distractor processing in HL compared to LL conditions was not observed. Instead there was a numerical trend for increased distraction under HL conditions. This effect was replicated in Experiment 3. The combined analysis of distractor effects in Experiments 1 and 3, revealed that this trend for increased distraction became significant in the error rate data, providing support for more distraction in the HL compared to the LL conditions. Previous studies of cross–modal PL have been mixed, however the findings of the current experimental series are in line with previous reports of either no effect or an increased effect of distraction in a HL compared to a LL condition (e.g., Jacoby et al., 2012; Muller–Gass, Stelmack & Campbell, 2006; Parks, Hilimire, Corballis, 2011; Rees, Frith, & Lavie, 2001, Experiment 2; Tellinghuisen & Nowak, 2003; Vroomen et al., 2001).

Importantly, neither of the two previous studies that have examined the effects of PL on cross–modal selective attention using a compatibility measure have found evidence for decreased distractor processing in the HL condition (Tellinghuisen & Nowak, 2003; Vroomen et al., 2001). Given that compatibility measures are most often used to assess PL in the uni–modal domain (Benoni & Tsal, 2013), it was deemed important to examine cross–modal PL effects using a similar measure. However, one potential issue with using compatibility measures, is that early selection theories of selective attention (e.g., Broadbent, 1958) suggest that while all stimuli are processed at the perceptual level, they are not all selected for further semantic processing. Thus, one potential explanation of the absence of modulation of load on distractor effects was that the previous two studies just examined *compatibility* measures. In other words, distractor modulation may have occurred at the perceptual level, but this would not be observed by a compatibility measure. Given that studies of cross–modal PL rely on a null effect of distractor modulation to infer independent resources, it is important to use a stronger test of independence. Thus in Experiment 3 of the current dissertation, in addition to compatibility effects, a detection measure was also employed, and importantly, this measure only required participants to detect a distractor in the second modality with no requirement of semantic processing. The detection data failed to show any decrease in sensitivity as the PL increased from LL to HL, providing further support for independent resources across modalities. However, the observed trend for increased distraction in the HL compared to the LL conditions in the compatibility measure was not observed in the detection measure. One potential explanation is that attention is object based in the cross–modal domain (Giard & Perronet, 1999; Molholm, Martinez, Shpaner & Foxe, 2007), and thus when distractor processing was increased it was limited to distractors that were thought to represent the same object as the target modality. For the compatibility measure the distractor had the potential for a semantic relationship with the target, however for the detection measure the distractor had no semantic relation to the target as the detection stimuli were bursts of noise in the visual or auditory domain. As such, the presence of a trend for increased distraction in the compatibility data, but not the detection data, may be related to the object based nature of cross–modal attention.

The finding of no modulation in the detection data based on PL in Experiment 3 is in direct contrast to a recent study by Raveh and Lavie (2015), who also used signal detection theory to assess the impact of PL on a visual search task on the detection of an auditory tone. In this study the authors found that under increased PL on the visual search task, there was a reduction in sensitivity to the auditory tone. One potential explanation for this finding is the use of a set size manipulation by Raveh and Lavie (2015). While there is also concern about this particular manipulation in the uni–modal domain (e.g., Tsal & Benoni, 2010) such that increases in set size leads to potential dilution effects (see Chapter 1), under conditions of capacity limitations arising at the modality level the dilution account is unlikely to apply to the cross–modal domain. Specifically a dilution account suggests that the non–target items that are present only in the visual HL display may dampen the representation of the distractor item causing the observed decrease in distractor effects. However, this explanation is less likely in the cross–modal case, especially under the assumption of independent processing resources as the non–target items in the HL condition are visual and thus if resources are independent then we may not expect dampened representation of the distractor modality. Instead, in the cross–modal domain, the concern regarding the use of a set size manipulating is based on the capacity for audio–visual integration. However, one factor that is thought to promote distraction in cross–modal conditions is integration of information from the two modalities (Chen & Spence, 2010). In a recent paper by Van der Burg, Awh and Olivers (2013) the authors suggest that audio–visual integration is limited to one item, specifically, that a single auditory stimulus can only be integrated with a single visual stimulus. While there is some debate as to whether increased presentation duration can increase this capacity (Wilbiks & Dyson, unpublished), the duration of the stimuli presented by Raveh and Lavie (2015) was 100 ms, which in both Van der Burg et al., (2013) and Wilbiks and Dyson (unpublished) led to a capacity limit of audio–visual integration to one item. Thus in the case of Raveh and Lavie, it may be that given multiple visual items and a single auditory item in the HL condition, the auditory item may be integrated with one of the non–target visual items, decreasing integration with the visual target and thus leading to reduced distraction effects.

Overall the data from the current experimental series provides consistent support for a lack of reduction in HL compared to LL conditions, and in fact shows evidence that distraction increases in HL conditions. Thus, while PLT can provide a resolution to the early vs late selection selective attention theories of uni–modal selective attention, it does not appear to apply to the cross–modal domain. Specifically, the evidence in the current dissertation does not provide any evidence that capacity limits exist at the supramodal level, and as such PLT cannot apply to the cross–modal domain. While there have been studies of cross–modal selective attention that have found support for the application of PLT to the cross–modal domain (e.g. Dyson, Alain & He, 2005, Experiment 2; Haroush, Hochstein & Deouell, 2009; Klemen, Buchel & Rose, 2009Macdonald & Lavie, 2011; Mulligan, Duke, & Cooper, 2007; Sinnett, Costa, & Soto–Faraco, 2006, Experiment 1; Toro, Sinnett & Soto–Faraco, 2005), none of these studies used compatibility effects. As discussed by Raveh & Lavie (2015) the conflicting cross–modal literature with respect to the application of PLT suggests that it is important to determine under which situations resources are shared/independent across modalities. Indeed, in the current dissertation, as well as the studies of Tellinghuisen & Nowak, (2003) and Vroomen et al. (2001), all of which have assessed cross–modal PL via manipulations of compatibility between target and distractor information, distractor processing is not reduced under HL conditions. Thus the current dissertation suggests, that in terms of semantic level representations, processing resources are independent across modalities.

Independent processing resources across the modalities provides an explanation of why the expected decrease in distractor processing from LL to HL conditions was not present. However, independent resources alone cannot explain the evidence supporting an increase in distraction in the HL condition. A consideration of this finding will be presented in the following section, where the impact of data and capacity limited processing is compared.

Data and capacity limits have the same impact on cross–modal distractor processing

In the uni–modal domain there is evidence that data and capacity limits (Norman & Bobrow, 1975) have opposite effects on distractor processing, such that while capacity limits led to a decrease in distraction, data limits do not (Lavie & de Fockert, 2003; however see Benoni & Tsal, 2012). In the current experimental series no support for such a dissociation was found. In Experiment 3 in which data and capacity limitations were directly contrasted within a single experiment, there was no evidence for any differences in distractor processing under these two conditions. In Experiment 3, a single manipulation was used to create data and capacity limited conditions. Confidence that Experiment 3 was indeed successful in promoting both data and capacity limited conditions can be gleaned based by comparing performance on the HL condition in Experiment 3 with the HL condition in Experiment 1, and, by comparing performance on the SD condition in Experiment 3 with the SD condition in Experiment 2. As can be seen in Table

3, there are striking equivalences in accuracy across the experiments for both capacity and data limited conditions. Thus, thus use of a single manipulation to promote data and capacity limited processing can be considered a strength of Experiment 3 as it rules out any alternative accounts of potential differences between these conditions being based on differences in the effects of the manipulations (Yeshurun & Marciano, 2013).

Table 3. Overall Accuracy (%) across each experiment, collapsed across congruency.

	LL		HL		SD	
	AA	AV	AA	AV	AA	AV
Experiment 1	6.9	4.5	7.9	5.8	—	—
Experiment 2	*6.8*	*3.4*	—	—	*26.3*	*23.4*
Experiment 3	*4.1*	*1.5*	*7.5*	*16.5*	*26.9*	*25.5*

Note: LL = Low Load, HL = High Load, SD = Sensory degradation

While the overall data in Experiment 3 provided support for trends of increased distraction in the HL compared to LL conditions in both modalities, the evidence in support of increased distractor processing in the SD compared to LL condition was only found in the attend–vision conditions. As discussed in Chapter 4, this likely rests in the design of the attend–audio SD condition. Specifically, in this condition the earliest the 'up/down' response could be selected was 600 ms following the onset of the stimulus (compared to 400 in LL and 500 in HL). Given that the visual stimulus was only presented for 525 ms, this large temporal gap between resolving the visual stimulus (at least 525 ms) and resolving the auditory stimulus may not have promoted cross–modal integration and thus reduced distractor effects. A comparison of the results in Experiments 1 and 2 can substantiate this claim, as well as the pattern of increased distraction under both HL and SD conditions, and no difference between HL and SD conditions. As such, a cross–experiment analysis was conducted with the data from Experiments 1 and 2.

Looking across these experiments, Experiment 1 revealed a trend for increased distraction under HL conditions, and Experiment 2 revealed a significant increase in distraction under SD conditions. Neither of these effects was contingent on attended modality. Furthermore, a cross–experiment analysis was conducted on the distractor scores in the HL condition of Experiment 1 and the SD condition for Experiment 2. The results revealed no significant differences in distraction across HL or SD conditions.

Importantly, Experiments 1 and 2 were very similar in terms of the design and the stimuli used, and only differed with respect to the manipulations of PL and SD. The PL manipulation used a go–no–go task that varied in difficulty across LL and HL, and in the SD condition, white noise was added to the target in degraded conditions. Importantly, these are both typical manipulations of PL and SD that are used in the literature, and the results of these manipulations produce results similar to Experiment 3. Thus overall, the current dissertation provides consistent evidence in favour of data and capacity limits having similar impacts on distractor processing.

There is currently debate as to whether data and capacity limits led to differing effects of distraction in the uni–modal domain (Lavie & de Fockert, 2003; Benonni & Tsal, 2012). While the current experimental series provides strong support that such a dissociation does not exist in the cross–modal domain, this does not necessarily imply that this dissociation is unlikely to apply in the uni–modal domain. Specifically, within a modality it is expected that there is a limited capacity (Norman & Bobrow, 1976), and thus there may be a distinction in the uni–modal domain on the impact of this capacity limit and data limits on selective attention. However, under conditions of independent resources across modalities, capacity limits need not have the impact of decreasing distractor processing in the secondary modality.

In terms of data limits, observations of increased distraction were expected based on theory (Meredith & Stein, 1983; Ernst & Banks, 2002) and empirical evidence of increased distraction under cross–modal selective attention (Yuval–Greenberg & Douelle, 2009; Collignon et al., 2008). Specifically, the principle of inverse effectiveness suggests that the weaker a signal is when presented in isolation, the greater the likelihood of integration is when that signal is presented with information in a secondary modality. While initially conceptualized based on single cell recordings, this principle has also been successfully applied to behaviour (Meredith & Stein, 1988). Furthermore, in addition to being more likely to integrate when the target signal is weak, sensory weighting shifts towards the intact information, which in the current dissertation was the distractor modality. These findings coupled with the large body of evidence which suggests that selective attention is more difficult when there is a greater likelihood of integration, provides a strong explanation of the observed increase in distraction in the SD conditions.

If capacity is not limited at the supramodal level, as is suggested by the observation of increased distraction under HL conditions, then it stands to reason that similar processes to those that occur in the SD condition would occur in the HL conditions. In the uni–modal domain the putative reason that distraction goes down in the HL case, is that although the task is more demanding, it can still be performed, so additional resources are placed on the target. Placing additional resources on the target under capacity limited conditions necessarily means that those resources cannot be placed on other potentially informative information in the environment. In the cross–modal domain however, once the target task is demanding, there is no harm in increasing the scope of attention to the distractor modality, as this does not impact available resources in the target modality. Furthermore, it is not unreasonable to consider that although not degraded, the target representations in the HL conditions in the current dissertation were nonetheless weaker than those in the LL conditions. For example in Experiment 3, the representation of the concept 'up' would likely have been weaker in the HL compared to LL condition, given that the distinction between either the 'up' or 'down' arrows being longer would have been smaller in the LL condition. Similarly, in Experiment 1, the representation of the concept of 'cat' would likely be weaker based on the concurrent circle/ellipse judgement being more taxing than in the LL condition. Thus according to the principle of inverse effectiveness, we would expect greater integration in the HL compared to the LL condition. The principle of inverse effectiveness is based on the processing efficiency of a uni–modal signal, and we did not have any uni–modal conditions in Experiment 1, so cannot provide empirical evidence that presented on its own, the HL task would be processed less efficiently than the LL task. However, there was a uni–modal condition in Experiment 3, and here there was evidence to suggest that for each modality, processing efficiency went down as difficulty went up (see Experiment 3 manipulation check in Chapter 4).

Overall, the current experimental series demonstrates, for the first time, that a single manipulation can be used to promote data and capacity limited conditions. Furthermore, taken together, the data from all three experiments suggests that data and capacity limits represent general increases in task difficulty that both result in increased distractor processing.

The impact of attended modality on cross–modal distractor processing

In the current experimental series there were two main effects of attended modality that emerged. The first was in Experiment 2, in which there was an observation of different patterns of distractor modulation based on attended modality, such that only facilitation effects were modulated in attend–audition conditions and only inference effects were modulated in attend–vision conditions. The second effect was observed across all experiments, such that audition had a trend for, or had significantly, more distraction than vision. These effects will be discussed in turn below.

Facilitation and interference effects

In Experiment 2, during attend–audition conditions there was greater facilitation in the attend–audio degraded condition compared to the intact condition. Conversely, during attend–vision conditions there were greater interference effects in degraded compared to intact conditions. The pattern of results obtained in the attend–vision condition mimics effects reported in a previous investigation on the influence of visual degradation on auditory distractor processing (Yuval–Greenberg & Douelle, 2009). In this study the authors also observed that only interference effects increased under conditions of visual target degradation, while facilitation effects did not differ across intact and degraded attend–vision conditions. As discussed in Chapter 3, this effect may be explained by the use of a bi–modal baseline in the current study and the study by Yuval–Greenberg & Douelle (2009), as research has shown that vision is facilitated by the presence of an auditory stimulus, while audition is interfered with by the presence of a visual stimulus (Sinnett, Soto–Faraco and Spence, 2008). Specifically, the authors found greater processing efficiency in cross–modal compared to uni–modal attend–vision conditions and decreased processing efficiency in cross–modal compared to uni–modal attend–audio conditions. Thus since both interference and facilitation effects are computed via a subtraction involving the neutral trials, it may be the case that vision does not see any additional facilitation based on a congruent auditory stimulus, and audition does not see any additional interference based on an incongruent visual stimulus (see Chapter 3 Discussion for a more detail).

Experiment 2 did not have any uni–modal conditions, and thus this potential explanation could not be tested. In Experiment 3 of the current dissertation, while there were no neutral trials, there were both uni–modal and cross–modal conditions. Thus in the cross–experiment analysis, processing efficiency across uni–modal and cross–modal conditions were compared for each modality. The results of this analysis revealed that visual responding was significantly faster in the cross–modal compared to the uni–modal condition, while auditory responding was significantly slower in the cross–modal condition compared to the uni–modal condition. However, the accuracy data did not show any significant differences between processing efficiency for uni–modal or the cross–modal conditions for either attend–audio or attend–vision. That the differences between uni–modal and cross–modal processing in Experiment 3 were only seen in the RT data is interesting given that differences in facilitation and interference in Experiment 2 were only seen in the error rates. Thus, while within the current experimental series there is some evidence to suggest that the impact of a bi–modal baseline may depend on the attended modality, this cannot provide a full account of the differences between facilitation and interference observed in Experiment 2. Future studies that include neutral trials in order to assess facilitation and interference, and contain uni–modal and cross–modal conditions can provide greater insights into the impact of uni–modal versus cross–modal baselines on resultant patterns of facilitation and interference.

Magnitude of distractor effects

Across all three experiments in the current dissertation, there were observations of greater distraction during attend–audition compared to attend–vision conditions. In all three experiments RT data revealed either a trend for (Experiment 1) or significantly greater (Experiments 2 and 3) distraction in attend–audition conditions. Furthermore, in Experiments 1 and 2, error rates revealed significantly greater distraction in attend–audition compared to attend–vision. One potential explanation for this finding is that these effects arise due to vision being faster than audition, which – based on horse–race accounts (e.g., Mordkoff & Yantis, 1991) – would cause greater distraction by visual compared to auditory distractor stimuli. However, there is also evidence to suggest the each modality is more appropriate than others for specific types of processing, and in this case the more appropriate modality will cause greater distraction (Welch & Warren, 1980). The impact of processing efficiency and modality appropriateness will be discussed in turn.

Processing efficiency

An examination of the aggregate data in Experiments 1 and 2 in which the neutral trials provide a measure of baseline responding in the absence of distractor effects, provides some support for the role of processing efficiency in determining the extent of distraction. In Experiment 1, baseline responding was faster for vision compared with audition and there was a trend for increased distraction for attend–audio conditions. However, the baseline error rate data do not reveal any differences between audition and vision, yet there was greater distraction in attend–audition. Thus Experiment 1 provides only partial support for a processing efficiency account. In Experiment 2, the error rate data reveal less efficient baseline processing in attend–audition, as well as increased distraction in attend–vision, providing support for the role of processing efficiency. The RT data in Experiment 2 provide a unique situation, as this was the only condition in which there was an interaction of modality and condition in baseline responding. Specifically, while audition was slower in intact conditions it was not so in degraded conditions. Based on a processing efficiency account, we would expect then to observe increased distraction for audition in the intact but not the degraded condition. However, this was not the obtained pattern of data. Instead, the distraction data revealed only a main effect such that audition had more distraction that vision, but this did not interact with condition.

The aggregate data provides partial support for the role of processing efficiency (PE) in determining which modality will receive greater distraction. In addition in both Experiments 1 and 2, an individual differences approach was used to determine if the relative efficiency of processing for audition and vision for each participant would correlate with the amount of distraction they received. Experiment 1 provided some support for the role of processing efficiency via a positive correlation of our PE measure and distraction in the attend–audition HL condition, however there were no correlation in the other conditions. In Experiment 2, there was an overall stronger effect of PE, as significant correlations appeared in both the auditory and visual modalities, as well as in both intact and degraded conditions (see Table 1 in Chapter 3). All of the significant correlations supported a processing efficiency account of distraction with greater distraction occurring from visual compared to auditory distractors, when there was greater disparities in the relative speeds of processing for audition and vision in favour of vision.

Overall there is support in both the aggregate and individual differences data to support a role of processing efficiency in determining the magnitude of distraction effects across modalities. Such a processing efficiency account also supports the role of inverse efficiency in cross–modal selective attention, as targets with decreased processing efficiency should be more likely to integrate other available information, and as a result experience greater distractor effects. However, processing efficiency cannot provide a full account, as there was not a consistent pattern in which PE correlated with the extent of distraction in all conditions. This suggests that the effects of PE are modulated by other factors such as the difficulty of the task, as correlations were not consistent across conditions.

Modality appropriateness

In addition to the impact of the relative PE of each modality in determining the extent of distraction it imposes on target processing, in the cross–modal domain certain types of stimuli/tasks are better suited to one modality over another (modality appropriateness hypothesis: Welch & Warren, 1980). In Experiment 1 and 2 naturalistic objects stimuli were used, and there is research to suggest vision is the dominant modality for object processing (e.g., Logothetics & Sheinberg, 1996). Thus, one account of the greater distractor effects for the auditory compared to the visual modality in these studies may be due to visual dominance in object processing. There is some support for this notion in the cross experiment analysis. Specifically, in the cross experiment analysis of Experiment 2 and 3, in both the RT and error rate data there was an experiment by modality interaction. In both cases this interaction arose from attend–audition conditions suffering from greater distraction in Experiment 2 relative to Experiment 3, while distraction was not different across these experiments for attend–vision conditions. This suggests that in Experiment 2, in which naturalistic stimuli were used, audition received greater interference than it did in Experiment 3 in which naturalistic stimuli were not used. This effect cannot be explained by a PE account as the relative speeding of vision over audition was actually greater in Experiment 3 compared with Experiment 2, and thus by a PE account, audition should have received more distraction in Experiment 3.

Finally the cross–experiment analysis of Experiments 2 and 3 revealed evidence that modality dominance interacts with SD. Specifically, in the cross–experiments analysis of Experiments 2 and 3 there was an interaction of experiment and condition, such that Experiment 2 revealed larger distractor effects than Experiment 3, however this was only apparent in the intact condition. This suggests that the effects of modality dominance were reduced when the targets were degraded in Experiment 2, thus leading to equivalent distraction effects across the two experiments in the degraded conditions. This effect is supported in the literature as Yuval–Greenberg and Douelle (2009) found that the visual dominance that was revealed in an intact condition was significantly reduced under degraded conditions.

Overall these results suggest that modality appropriateness does impact the extent of distraction and supports the view that vision is the dominant modality for object processing. In addition there is evidence that modality dominance is impacted by task demands, such that the effects are weakened under degraded conditions.

The impact of individual differences in attentional control on cross–modal distractor processing

In the current dissertation individual differences in attentional control were evaluated by correlating participants' performance on the executive control measure of the ANT with the main distractor task in Experiments 1 and 2. Previous research suggested conditions that are capacity limited would not see any effects of individual differences in attentional control as all resources would be placed on the target task, and thus no spare resources would be available for distractor processing, eliminating the need for attentional control. Thus the current dissertation sought to determine if this effect would also be observed in the cross–modal domain. Moreover, no study has assessed possible interactions of the impact of ID in attentional control SD. The results of Experiments 1 and 2 provide very limited support for a role of individual differences in uni–modal attention on cross–modal attention, and provide no support that the impact of individual differences are modulated by task demands.

Significant correlations between participants' performance on the ANT and distractor scores on the main task were only found in Experiment 1, and only in the attend–audio conditions. As discussed in Chapter 2, this finding suggests that there are differences in uni–modal and cross–modal selective attention, as correlations were not found in the attend–vision conditions. Furthermore, the significant correlations in the attend–audio condition for both LL and HL suggest that any effects of individual differences in attentional control are not impacted by the difficulty of the target task. No significant correlations were found between the ANT and the main target task in Experiment 2.

The ANT task was used in order to have an independent measure of selective attention that could be correlated with our main distractor tasks in Experiments 1 and 2. In particular I was interested in determining how individual differences interacted with factors such as SD and increased PL. However, the overall lack of significant correlation suggest that there are important differences in attentional control within and between modalities. Thus the current experimental series cannot offer strong insights into the role of individual differences in cross–modal selective attention. However, the results are instructive in providing further support that there are differences in uni–modal and cross–modal selective attention.

General conclusions and future directions

The current dissertation aimed to assess the impact of various factor on cross–modal selective attention. The experimental series revealed 4 main conclusions. First, resources are independent across modalities. Second, data and capacity limits both have the effect of increasing distractor processing. Third, the attended modality impacted selective attention, and this was due in part to the relative processing efficiency of each modality, and the relative appropriateness of each modality in processing the specific stimuli used. Finally, little evidence was found for correlations between cross–modal and uni–modal selective attention in terms of individual differences in attentional control. Future research should continue to compare the impact of factors such as PE, modality appropriateness, and individual differences in attentional control and how these interact with factors such as data and capacity limits. Studies which manipulate PE and modality appropriateness could build upon the current findings by systematically investigating the impact that these factors exert on cross–modal selective attention, under various task demands (LL, HL and SD). Future studies should also focus on the role of individual differences by employing two independent cross–modal selective attention tasks and determining if there are consistent patterns across participants' performance on the two tasks. Finally, to further substantiate the finding in the current dissertation that data and capacity limits can be reached with a single manipulation, and have the same impact on cross–modal distractor processing, future research could employ a design in which a single manipulation was used to promote data and capacity limits, and in addition another data limited condition using traditional methods could be included provide strong empirical evidence that both data limited conditions led to a similar pattern of performance, and that these conditions did not differ from a capacity limited condition in terms of observed patterns of distractor processing.

Overall the current dissertation suggests that a main determining factor regarding the success of cross–modal selective attention is the likelihood to integrate information across the senses. However, in the current dissertation, the contribution of the likelihood to integrate and PL and SD cannot be parsed apart as SD conditions, and potentially HL conditions, promote integration (Meredith & Stein, 1983; Stein & Meredith, 1988). Thus one potentially interesting avenue for future research would be to pit the likelihood of integration against manipulations of PL and SD, to determine which has a stronger impact on cross–modal selective attention. For example a future study could manipulate PL and within each PL condition could also manipulate temporal and spatial correspondences. Such an experiment would be well suited to parse apart the contributions of PL/SD versus factors that promote integration (temporal and spatial correspondences) thereby contributing to an increasingly complete understanding of the factors that contribute to cross–modal integration.

Appendix A. Experiment 2a: Stimulus Selection

Introduction

Experiment 2a was conducted to choose an appropriate method and degree of SD. There are various methods of SD that are used in the auditory and visual domain. For example, in vision studies researchers can degrade visual perception via manipulations such as adding noise (e.g., Nath and Beauchamp, 2011), blurring (e.g., Owens & Tyrrell, 1999; Alais and Burr, 2004), lowering the contrast (e.g., Yuval–Greenberg & Deouell, 1999) decreasing the size (e.g., Lavie and De Fockert, 2003), induced myopia (Hairston et al., 2003) or reducing visual acuity based on position eccentricity (e.g., Lavie and De Fockert, 2003). Likewise, there are various routes to stimulus degradation in the auditory domain including adding noise (e.g., Nath and Beauchamp, 2011; Ma et al., 2009; Sumby and Pollack, 1954), reducing intensity (e.g., Sandhu and Dyson, 2012), adding reverberation (e.g., Gordon–Salant, & Fitzgibbons, 1999) or by applying time compression (e.g., Gordon–Salant, & Fitzgibbons, 1999). While there are clearly many means of SD available in either the visual or auditory modality, one important factor in selecting a method for the proposed study is that there be a similar form of degradation available in both modalities (e.g., Nath and Beauchamp, 2012; Noppeney et al., 2010). Specifically, the two methods of degradation selected were a) the addition of noise, and, b) visual contrast reduction / auditory intensity reduction. Both were viewed as analogous processes across vision and audition, and, both had the similar effect of reducing the saliency of the stimuli without any distortion effects.

Methods

Participants

24 healthy adults (age 18–45) from Ryerson University and the Toronto area were be recruited.

Stimuli and Design

For each SD technique, there were be 5 levels of stimulus degradation. In the visual noise condition, white Gaussian noise (0%, 100%, 133%, 166%, or 199%) were added to the stimulus. In the auditory noise condition auditory stimuli were also be presented with white Gaussian noise. Different amounts of noise needed to be added to each sound in order to equate for subjective difficulty (based on experimenter). Thus the range of added white Gaussian noise across all stimuli was 4% – 110%, and noise was added using MATLAB software. Although there is large variation in the amount of noise added to subjectively equate for difficulty, given that all stimuli will be presented an equal number of times in all conditions, any slight differences in difficulty for a given object should not systematically influence the results. In the contrast/intensity reduction conditions auditory stimuli were presented at 6%,10%, 14%, 18% or 100% intensity, and visual stimuli were presented at 8%, 8.5%, 9%, 9.5% opacity. Stimuli were presented audio–visually. However, in the attend–vision condition, the auditory stimuli were always neutral tones and in the attend–audition condition the visual stimulus were always neutral images. Stimulus degradation was manipulated using one of two methods (noise addition, contrast/intensity reduction), and the task was to identify an object at the basic level of categorization (e.g., ‘dog’).

Thus the design was a 2 (attended modality; audition, vision) x 2 (stimulus degradation technique; noise, contrast) x 5 (degradation level: 1, 2, 3, 4, 5) factorial design with 20 conditions. Modality and stimulus degradation technique was blocked such that in any given block participants attended to either auditory or visual information, and stimuli were either noise degraded or contrast/intensity degraded. Each of the four blocks (auditory intensity (AI), auditory noise (AN), visual contrast (VC), visual noise (VN)) consisted of 150 trials (30 trials for each level of stimulus degradation, with two presentations of each degradation level per object), leading to a total of 600 experimental trials. Prior to each block, participants had 12 practice trials that were randomly selected from the full corpus of 150 trials. Trial order was randomized per participant and block order and button–box response mapping was counter–balanced across participants.

Procedure

Participants will complete one run of each of the four blocks and will be offered breaks between blocks. Block order will be counterbalanced across participants. The entire experiment including consent and debriefing was completed within one hour.

Results

Median reaction times, and percentage error were calculated for each level of stimulus degradation in each of the 20 conditions. A 2 (attended modality; audition, vision) x 2 (stimulus degradation technique; noise, contrast) x 5 (degradation level: 1, 2, 3, 4, 5) repeated measures ANOVA was conducted independently on reaction time and arcsine transformed error rate data. All post hocs were conducted using Tukey's HSD at the .05 level.

RT Analysis

The 3 way ANOVA on RTs revealed a main effect of modality: $F(1,23) = 18.80$, $p < .001$, $\eta^2_p = .450$, demonstrating faster RTs to visual (714 ms) compared to auditory stimuli (848 ms). A main effect of degradation method: $F(1,23) = 8.78$, $p < .01$, $\eta^2_p = .276$, revealed greater slowing associated with the noise (819 ms) compared with the contrast/intensity (744 ms) manipulations. Finally a main effect of degradation level: $F(4, 92) = 21.98$, $p < .001$, $\eta^2_p = .489$ demonstrated the lowest RTs to the intact conditions (711 ms) which generally increased as the degradation manipulation increased (774 ms, 794 ms, 794 ms, 832 ms from level 2–5 respectively). Post hoc analysis revealed that the intact level and the most difficult level (level 5) were significantly different from each other and all other levels. However, the intermediate levels (levels 2, 3 and 4) were not significantly different from one another.

The interaction between degradation method and degradation level was significant: $F(4,92) = 4.79$, $p < .01$, $\eta^2_p = .172$. This interaction revealed that while the intact and most difficult levels were significantly different from each other and all other levels when using the noise manipulation. In contrast, when using the contrast and intensity manipulation, only the most difficult level was significantly different from all other levels, with the intact and intermediate levels (2, 3,4) all being statistically equivalent in terms of RTs. All other interactions were non-significant, all *p*s >.199, all η^2_p s < .063.

Error rate Analysis

A main effect of degradation type: $F(1,23) = 17.17$, $p < .001$, $\eta^2_p = .366$, in line with RT data, revealed greater errors associated with the noise (16.08 %) compared to the contrast/intensity (12.06%) manipulations. A main effect of degradation level: $F(4,92) = 118.88$,

p <.001, η^2_p = .820 showed an increase in error rate as the degradation manipulation increased (6.95%, 10.35%, 13.92%, 17.40%, 21.74% from levels 1–5 respectively), with post–hocs showing that all levels were significantly different from each other (all *p*s < .001).

All two-way interactions were subsumed by a significant three–way interaction between the factors of modality, degradation method and degradation type, $F(4,92) = 6.55$, $p < .001$, η^2_p = .506. Post hoc analysis revealed that the intact noise level was significantly different from all other levels for both auditory and visual conditions. However in the audio noise condition the only other difference between levels was that between levels 2 and 5, while for visual noise condition all levels were significantly different from one another except level 4 and 5. For the contrast/intensity conditions, the intact auditory condition was only significantly different from level 2, while the visual contrast condition the intact level was significantly different from levels 3, 4, and 5 and level 5 was also significantly different from levels 3 and 4.

Discussion

Experiment 2a was designed to select a degradation method that would led to a decrement in performance across various levels of degradation manipulations, while leading to similar patterns of degradation across audition and vision. Based on the findings of study 2a, noise addition was selected as the more appropriate degradation method.

The key factor in choosing the noise manipulation was the fact that the intact noise condition for both audition and vision, led to significantly better performance than all other degradation levels both in terms of RTs and error rates. This was not the case for the contrast/intensity manipulations, where the RTs (relative to the intact level) were only slowed at the highest degradation level. Furthermore, for the contrast/intensity manipulation, level 2 had a significantly lower error rate than the intact condition, suggesting that this level of degradation actually improved performance relative to the intact condition.

A second factor in selecting a degradation method was that there be similar performance decrements associated with increasing degradation across both audition and vision. Although there was a main effect of modality, which showed that vision was generally faster than audition, there was no interaction with modality and degradation level in the RT data showing that both the noise/intensity manipulations did show a similar magnitude of performance decrement across the degradation levels for both modalities. However, the overall difference in RTs was numerically lower in the noise (119 ms) than in the contrast/intensity conditions (150 ms), although this effect was non-significant (modality x degradation method: $F(1,23) = .34$, $p=.56$).

Thus the results of this study point to the noise manipulation being the more suitable degradation method for the current experimental series. While the current experiment clearly favors noise over contrast/intensity manipulations, a further experiment will be conducted to choose the specific two levels of noise for each modality. While currently there are no significant differences between levels 2–4 in terms of RT's, there is a trend for increased RT with increased error rate. In Experiment 2b a further manipulation will be added to the stimulus (discussed below) and thus Experiment 2b will be conducted just with the noise manipulations and levels used in the current study, but will include an addition task/stimulus manipulation.

Appendix B: Full analyses of Experiment 3 detection task with inclusion of the uni–modal condition

d′

d′ was calculated by subtracting the z score of the false alarm rate, from the z score of the hit rate (Green & Swets, 1966). Only trials in which the main target task response was correct were included in d′ analysis (after Raveh & Lavie, 2015). d′ values were then entered into a 2 (Condition: uni–modal, cross–modal) x 2 (attended modality: auditory, visual) x 3 (difficulty: LL, HL, SD) repeated measures ANOVA. The results revealed a significant main effect of difficulty F (1,46) = 10.10, MSE = 4.5, $p < .001$, $\eta^2_p = .305$, and significant interactions between difficulty and modality; F (2,46) = 10.39, MSE = 4.44, $p < .001$, $\eta^2_p = .311$, and between modality and condition; F (1,23) = 36.87, MSE = 42.65, $p < .001$, $\eta^2_p = .616$.

Regarding the main effect of difficulty, follow up tests indicated that while sensitivity remained stable across LL (3.23) and HL (3.17) conditions, it decreased significantly from both of these conditions to the SD condition (2.82). The interaction of modality and difficulty revealed that the decrease seen in the SD condition in the main effect of difficulty is driven by the auditory modality. Specifically, sensitivity is significantly lower in the attend–audio SD (2.54) condition, relative to either the LL (3.38) or HL (3.15) conditions which did not differ significantly from each other. There were no significant differences in sensitivity across difficulty conditions in attend–vision (LL = 3.10, HL = 3.19, SD = 3.11). Finally, the interaction between condition and attended modality revealed that the sensitivity in the UA (2.61) and CV (2.78) conditions did not differ from each other, nor did sensitivity in the UV (3.43) or the CA (3.49) conditions. This follows from the experimental design since in UA and CV the detection stimulus was identical (auditory detection stimulus) and in UV and CA the detection stimulus was identical (visual detection stimulus). This suggests that the detection of a visual or auditory stimulus is the same, regardless of which modality is attended. Considering attend–audition conditions, there was an increase in sensitivity from the UA condition (2.61) to the CA condition (3.49) which suggests that the visual detection stimulus (present in CA) was easier to detect than the auditory detection stimulus (present is UA). Conversely, comparing attend–vision conditions, there was a decrease in sensitivity from the UV condition (3.43) to the CV condition (2.78). Again this suggests that the visual detection stimulus (present in UV) was easier to detect than the auditory detection stimulus (present in CV).

Overall these data suggest sensitivity was greater for the visual compared to auditory detection stimuli. Importantly, sensitivity was not affected by difficulty in attend–vision conditions, however, in attend–audition conditions, sensitivity decreased at the most difficulty level (SD condition).

β

β was calculated using the formula: β = –d′×.5×(z(hits) + z(false alarms)) (Green & Swets, 1966). Only trials in which the main target task response was correct were included in β analysis (after Raveh & Lavie, 2015). Resultant data were then entered into a 2 (Condition: uni–modal, cross–modal) x 2 (attended modality: auditory, visual) x 3 (difficulty: LL, HL, SD) repeated measures ANOVA. A significant main effect of condition, F (1,23) = 38.96, MSE = 115.3, $p < .001$, $\eta^2_p = .629$, and attended modality emerged, F (1,46) = 4.97, MSE = 15.6, $p < .05$, $\eta^2_p = .178$, as did a significant interaction between condition and attended modality, F (2,46) = 17.81, MSE = 253.1, $p < .001$, $\eta^2_p = .436$. The main effects of condition and attended modality revealed that participants used a more conservative criterion in the cross–modal (U = 2.34, C =

3.60) and attend–audition (A = 3.20, V = 2.74) conditions. The interaction of condition and attended modality revealed that there was no impact of condition on performance in the visual detection tasks (UV =2.43, CV=1.63, respectively). However, there was an impact of condition on performance in the auditory detection task with stricter criterion in the CV (4.77) compared to UA (3.04) conditions. Comparing attend–audition conditions, the criterion was stable across uni–modal (3.04) and cross–modal (1.63) conditions, even though the detection stimuli were presented in different modalities. In contrast comparing the attend–vision conditions, the criterion increased from uni–modal (2.43) to cross–modal (4.77) conditions, suggesting that while attending to a visual target, the detection criterion is made stricter when the detection stimuli was auditory.

Overall the criterion analysis suggests that criterion was stable across all conditions with the exception of the CV condition which had a stricter criteria than all other conditions. Importantly, the lack of main effect or interaction with the factor of difficulty suggests that participants did not alter their criterion based on the difficulty level of the task, and thus any changes in sensitivity across difficulty levels cannot be accounted for by changes in criterion.

Discussion

It is noteworthy that in the current study in our uni–modal visual condition we did not find any differences in sensitivity as task difficulty increased. One potential explanation for this is that we used a non–set size manipulation of PL. Previous investigations that have used a non–set size manipulation have also failed to find the expected decrease during HL conditions (e.g., (Benoni & Tsal, 2010; Tsal & Benoni 2010; Wilson, Marois & MacLeod, 2011). The current study was not focused on PLT in the uni–modal domain, however future studies, which compare

HL and SD conditions uni–modally, with and without a set size manipulation can clarify if the lack of sensitivity modulation in the current study was due to the use of a non–set size manipulation.

The uni–modal attend–audio condition is the only one that shows a monotonic decrease in detection as difficulty increased from LL to HL and then to SD. This decline cannot be accounted for based on participants placing less priority on the detection task as the discrimination task became more difficult, as there were no significant changes in response bias across these conditions. Furthermore, in the current study, the detection stimulus in the uni–modal auditory condition was presented at 50–150 ms or at 250–350 ms. In both cases, the detection stimulus was presented prior to the offset of the short sound in all difficulty levels and so at the point of the detection stimulus presentation, the stimuli in all difficulty levels were identical. As such any changes in detection sensitivity must rely on post–perceptual processing of the detection stimulus only. However note that these cannot be decisional in that participants placed less priority on the detection response in the harder conditions given the lack of changes in response bias. One potential explanation is that as the minimum time before as response could be selected increased from LL to HL to SD conditions, the representation of the detection stimulus faded from memory. Given that any differences in sensitivity as a function of task difficulty in the uni–modal attend–audio condition are likely due to post perceptual processing, the uni–modal conditions were not included in the main analysis.

Appendix C. Consent and debriefing forms

Experiment 1 and 2

Monetary consent form:

Ryerson University Consent Agreement

AUDITORY AND VISUAL OBJECT RECOGNITION:
Attentional load and sensory degradation

You are being asked to participate in a research study. Before you give your consent to be a volunteer, it is important that you read the following information and ask as many questions as necessary to be sure you understand what you will be asked to do.

Investigators: Raj Sandhu (Student investigator, MA), Ben Dyson (Faculty Supervisor, PhD), Department of Psychology, Ryerson University

Purpose of the Study: This study is part of an ongoing research program where we hope to more fully understand the way in which the brain processes auditory and visual information, how information from different senses interact. We are hoping to test 80 healthy adults, and wish to use only those individuals who self-report as having normal (or corrected-to-normal) hearing and vision.

Description of the Study: The study will take place in the HEAR Lab, located in the Psychology Research and Training Centre at 105 Bond Street. As a part of the consent process, you will have the study explained to you and the opportunity to take part in a practice block so you are familiar with the procedure (note data will not be recorded during these practice blocks). You will be given the chance to ask any questions you may have regarding the study, prior to reviewing the consent agreement. After providing written consent, you will be asked for age, gender and handedness information. After the study, you will be fully debriefed as to the purpose of the study, and given a further opportunity to ask questions.

During both practice and the actual experiment, you will hear and/or see sounds, images and/or verbal labels associated with natural objects. For example you may hear the sound of a dog barking or see the image of a dog. The sounds will be presented over speakers placed behind the computer screen and the images will be presented on the computer screen. You will be told before each block if you should pay attention to what you hear or what you see, and if you should pay attention to verbal or non-verbal information. After the objects have been presented, you will be shown a response prompt where you will have to verify a particular feature of the object (e.g., the common name (i.e., dog) or higher level category (i.e., animal) of the object) by pressing one of two buttons on a response pad. However, you will only do this on some trials, based on a secondary stimulus presentation (either auditory or visual). In cases in which you respond to the response cue, your response to the response prompt will either be 'Yes' or 'No'.

On audio only or visual only trials, you will only hear something or see something. On trials in which you are presented with two pieces of information (e.g, sound and image, or image and a written word or sound and spoken word) the information may match (e.g., the sound of a dog barking and the image of a dog) or they may be different (e.g., the sound of a dog barking and the image of an airplane). Sometimes there will be no correspondence between the two. For example, you may hear be a scrambled sound that does not represent any particular object, or you may see be a scrambled image which does not represent any particular object.

What is Experimental in this Study: Previous research has been interested in how auditory and visual information interact with one another. We hope to extend this research by examining how attention interacts across the senses.

Risks or Discomforts: There are no known long-term risks associated with behavioral testing of the manner proposed. One short-term risk is fatigue. Effects of fatigue will be offset by providing participants with the opportunity to take breaks in-between blocks of trials. *If you feel uncomfortable at any time during the experiment, you may discontinue participation, either temporarily or permanently without penalty*

Benefits of the Study: The potential benefits of the study for science and society are a greater understanding of the similarities and differences involved in processing information from a single modality to processing and combining information from multiple modalities. However, there are no immediate benefits that you can reasonably expect from the study.

Confidentiality: Confidentiality will be maintained in all aspects of data dissemination. Only identifying information (name) will appear on this consent form. For all other aspects of the study, a unique numeric ID will be assigned for each participant. Names and IDs will not be matched. Original paper records will be stored in a locked file cabinet and electronic records will be stored on password-protected computers. All data will be stored for a minimum of 1 year after collection. Data is typically retained for 5 years after publication of the study with hardcopy data will be destroyed by confidential shredding; electronic data will be destroyed by deletion. Participants have the option of reviewing and / or removing all of their data from the study, if the request is made immediately after the study.

Incentives to Participate: Payment is offered for experimental participation at the rate of $10 per hour.

Voluntary Nature of Participation: Participation in this study is voluntary. Your choice of whether or not to participate will not influence your future relations with Ryerson University. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. At any particular point in the study, you may refuse to answer any particular question or stop participation altogether.

Questions about the Study: If you have any questions about the research now, please ask. If you have questions later about the research, you may contact.

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If you have questions regarding your rights as a human subject and participant in this study, you may contact the Ryerson University Research Ethics Board for information.

Research Ethics Board
c/o Office of the Vice President, Research and Innovation
Ryerson University, 350 Victoria Street
Toronto, ON, M5B 2K3, Canada
001 416-979-5042

Agreement: Your signature below indicates that you have read the information in this agreement and have had a chance to ask any questions you have about the study. Your signature also indicates that you agree to be in the study and have been told that you can change your mind and withdraw your consent to participate at any time. You have been given a copy of this agreement. You have been told that by signing this consent agreement you are not giving up any of your legal rights.

Informed consent for study participation

____
Name of Participant (please print)

____________________________________ __________________
Signature of Participant Date

____________________________________ __________________

Signature of Investigator Date

Student participation consent forms:

Ryerson University Consent Agreement

AUDITORY AND VISUAL OBJECT RECOGNITION:
Attentional load and sensory degradation

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What is Experimental in this Study: Previous research has been interested in how auditory and visual information interact with one another. We hope to extend this research by examining how attention and sensory degradation interacts across the senses.

Risks or Discomforts: There are no known long-term risks associated with behavioral testing of the manner proposed. One short-term risk is fatigue. Effects of fatigue will be offset by providing participants with the opportunity to take breaks in-between blocks of trials. *If you feel uncomfortable at any time during the experiment, you may discontinue participation, either temporarily or permanently without penalty*

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Incentives to Participate: Two different incentive schemes are offered. For individuals enrolled in introduction to psychology (102 or 202) at Ryerson University, course credit is available as an incentive, awarded either on the basis of participation or a walk-through in which the participant can take part in the study but not submit their data.

Please indicate which incentive you require:

☐ COURSE CREDIT (2%) (PARTICIPATION) ☐ COURSE CREDIT (2%) (WALKTHROUGH)

Voluntary Nature of Participation: Participation in this study is voluntary. Your choice of whether or not to participate will not influence your future relations with Ryerson University. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. At any particular point in the study, you may refuse to answer any particular question or stop participation altogether.

Questions about the Study: If you have any questions about the research now, please ask. If you have questions later about the research, you may contact.

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Toronto, ON, M5B 2K3, Canada
001 416-979-5042

Agreement: Your signature below indicates that you have read the information in this agreement and have had a chance to ask any questions you have about the study. Your signature also indicates that you agree to be in the study and have been told that you can change your mind and withdraw your consent to participate at any time. You have been given a copy of this agreement. You have been told that by signing this consent agreement you are not giving up any of your legal rights.

Informed consent for study participation

____
Name of Participant (please print)

____________________________________ __________________

Signature of Participant Date

Signature of Investigator Date

Experiment 3

Monetary consent forms:

RYERSON UNIVERSITY

Ryerson University Consent Agreement

AUDITORY AND VISUAL OBJECT RECOGNITION:
Attentional load and sensory degradation

You are being asked to participate in a research study. Before you give your consent to be a volunteer, it is important that you read the following information and ask as many questions as necessary to be sure you understand what you will be asked to do.

Investigators: Raj Sandhu (Student investigator, MA), Ben Dyson (Faculty Supervisor, PhD), Department of Psychology, Ryerson University

Purpose of the Study: This study is part of an ongoing research program where we hope to more fully understand the way in which the brain processes auditory and visual information, how information from different senses interact. We are hoping to test 80 healthy adults, and wish to use only those individuals who self-report as having normal (or corrected-to-normal) hearing and vision.

Description of the Study: The study will take place in the HEAR Lab, located in the Psychology Research and Training Centre at 105 Bond Street. As a part of the consent process, you will have the study explained to you and the opportunity to take part in a practice block so you are familiar with the procedure (note data will not be recorded during these practice blocks). You will be given the chance to ask any questions you may have regarding the study, prior to reviewing the consent agreement. After providing written consent, you will be asked for demographic information, as well as information regarding your history of brain injury. In addition we will ask to you complete a standardized test your cognitive functioning, as well as a standard vocabulary test. Finally, we will complete a nonclinical sight and hearing test. These tests and surverys will help us to characterize our participant sample. As with the rest of the study, completion of these tests/surveys is entirely voluntary. After the study, you will be fully debriefed as to the purpose of the study, and given a further opportunity to ask questions.

During both practice and the actual experiment, you will hear and/or see sounds and images. For example you may see an arrow and hear a tone that was increasing in pitch. The sounds will be presented over speakers placed behind the computer screen and the images will be presented on the computer screen. You will be told before each block if you should pay attention to what you hear or what you see. After the objects have been presented, you will be shown a response prompt where you will have to verify a particular feature of the object by pressing one of two buttons on a response pad.

On audio only or visual only trials, you will only hear something or see something. On trials in which you are presented with two pieces of object information the information may match or they may be different. Sometimes there will be no correspondence between the two.

What is Experimental in this Study: Previous research has been interested in how auditory and visual information interact with one another. We hope to extend this research by examining how attention and sensory degradation interacts across the senses.

Risks or Discomforts: There are no known long-term risks associated with behavioral testing of the manner proposed. One short-term risk is fatigue. Effects of fatigue will be offset by providing participants with the opportunity to take breaks in-between blocks of trials. *If you feel uncomfortable at any time during the experiment, you may discontinue participation, either temporarily or permanently without penalty*

Benefits of the Study: The potential benefits of the study for science and society are a greater understanding of the similarities and differences involved in processing information from a single modality to processing and combining information from multiple modalities. However, there are no immediate benefits that you can reasonably expect from the study.

Confidentiality: Confidentiality will be maintained in all aspects of data dissemination. Only identifying information (name) will appear on this consent form. For all other aspects of the study, a unique numeric ID will be assigned for each participant. Names and IDs will not be matched. Original paper records will be stored in a locked file cabinet and electronic records will be stored on password-protected computers. All data will be stored for a minimum of 1 year after collection. Data is typically retained for 5 years after publication of the study with hardcopy data will be destroyed by confidential shredding; electronic data will be destroyed by deletion. Participants have the option of reviewing and / or removing all of their data from the study, if the request is made immediately after the study.

Incentives to Participate: Payment is offered for experimental participation at the rate of $10 per hour.

Voluntary Nature of Participation: Participation in this study is voluntary. Your choice of whether or not to participate will not influence your future relations with Ryerson University. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. At any particular point in the study, you may refuse to answer any particular question or stop participation altogether.

Questions about the Study: If you have any questions about the research now, please ask. If you have questions later about the research, you may contact.

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If you have questions regarding your rights as a human subject and participant in this study, you may contact the Ryerson University Research Ethics Board for information.

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Ryerson University, 350 Victoria Street
Toronto, ON, M5B 2K3, Canada
001 416-979-5042

Agreement: Your signature below indicates that you have read the information in this agreement and have had a chance to ask any questions you have about the study. Your signature also indicates that you agree to be in the study and have been told that you can change your mind and withdraw your consent to participate at any time. You have been given a copy of this agreement. You have been told that by signing this consent agreement you are not giving up any of your legal rights.

Informed consent for study participation

____
Name of Participant (please print)

____________________________________ __________________
Signature of Participant Date

____________________________________ __________________
Signature of Investigator Date

Student participation consent forms:

Ryerson University Consent Agreement

AUDITORY AND VISUAL OBJECT RECOGNITION:
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Incentives to Participate: Two different incentive schemes are offered. For individuals enrolled in introduction to psychology (102 or 202) at Ryerson University, course credit is available as an incentive, awarded either on the basis of participation or a walk-through in which the participant can take part in the study but not submit their data.

Please indicate which incentive you require:

☐ COURSE CREDIT (2%) (PARTICIPATION)

☐ COURSE CREDIT (2%) (WALKTHROUGH)

Voluntary Nature of Participation: Participation in this study is voluntary. Your choice of whether or not to participate will not influence your future relations with Ryerson University. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. At any particular point in the study, you may refuse to answer any particular question or stop participation altogether.

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Informed consent for study participation

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Name of Participant (please print)

___________________________________ __________________
Signature of Participant Date

___________________________________ __________________
Signature of Investigator Date

All Experiments debrief form:

Ryerson University **Debriefing Form**

AUDITORY AND VISUAL OBJECT RECOGNITION:
Attentional load and sensory degradation

Dear Participant:

Thank you very much for you participation in our study. Your time and commitment to psychological research at Ryerson University is very much appreciated.

The study you took part in will contribute to ongoing auditory and visual research conducted in the H.E.A.R Lab. Our lab is dedicated to designing and implementing research studies that will help us better understand how the brain represents what we hear and see, and how this information is integrated.

The particular study you took part in was designed to assess how individuals cope with distraction (the information you attempted to ignore) when attempting to identify objects. In certain conditions the task you performed was harder than in other conditions. Also, sometimes the quality of the sounds and images were better than other conditions. We were interested in determing if the impact that the distractors had on speed and accuracy would be the same based on the difficulty of the task you were asked to perform and based on the quality of the target information.

If you have any questions regarding your participation in this study, or would like to receive information about the results once they are available, feel free to contact Raj Sandhu. We would be happy to provide you with the overall findings of our study.

Finally, if you are interested in taking part and learning more about visual and auditory perception research in the H.E.A.R Lab, feel free to contact Dr. Dyson.

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