

Selective attention in vision, audition and touch

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Abstract

Given that our perceptual capacity is limited, it is important that we are able to focus our attention selectively on certain stimuli at the expense of others in order to behave effectively in a world filled with sensory information. Here, we review evidence from behavioural and neuroscientific studies of this process of selective attention in vision, hearing, and touch. Our particular focus in this chapter is on the enduring debate over the stage of processing at which unattended information is excluded from further processing. The chapter describes the origins of this debate and highlights some of the most important empirical and theoretical work to have emerged from studies of this issue in recent years.

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1. Introduction

Our brains continuously receive huge amounts of sensory information concerning the busy and complex world in which we live. In fact, according to Koch and Tsuchiya (2007), primates receive somewhere in the order of a megabyte of raw information per second via their eyes alone. In order to make sense of all of this sensory input, and to act upon it appropriately, it is essential that we are able to focus our attention selectively on certain stimuli at the expense of others. For example, as you read this sentence, you will probably have been ignoring the feel of the clothes on your body (see Gallace & Spence, 2014; Graziano, Alisharan, Hu, & Gross, 2002) and any number of background sounds from the world outside. In this chapter, we consider the extent to which our brains can achieve such selectivity of information processing in the visual, auditory and tactile modalities and the means by which they might do so. Empirical evidence from many different experimental methodologies now supports the view that unattended sensory information is processed less thoroughly by the brain than is attended information. The results of numerous behavioural studies have demonstrated that unattended sensory inputs are perceived and/or remembered less successfully than attended information. From a neurophysiological standpoint, the attentional modulation of neural activity has now been observed in both humans and other animals. Here, we review the evidence from both of these lines of research, integrating the findings that have emerged from those studies that have examined the cognitive constraints on information processing in audition, vision, and touch – the

sensory modalities where attention has, to date, been most widely studied. We also draw out a number of the parallels in the mechanisms of selective attention as they affect the processing of information in these different spatial senses.

Our focus in this chapter relates to what has perhaps been one of the most enduring questions in the study of selective attention: namely, the stage of processing at which unattended information is excluded. It is generally agreed that all information must be processed to some level, so that it can, at the very least, be deemed as being either potentially relevant or else discarded as irrelevant. However, estimates of the extent to which unattended information is processed in the brain vary widely. The lively debate over this issue has continued apace for more than 60 years now and is still a topic of primary interest to a number of attention researchers even today. Below, we describe the origins of the debate and highlight some of the most important experimental evidence that has emerged over the years from studies of this issue in the modalities of audition, vision, and touch.

2. Behavioural Evidence for 'Early' Selection

Many of the earliest studies of attention focused on the selection taking place within the auditory modality. This research began in the early 1950s with the development of the dichotic listening paradigm (Cherry, 1953, 1954). The participants in these early studies were typically presented with two different auditory messages, one to either ear. They had to repeat out loud (that is, to 'shadow') the message presented to a specified ear while trying to ignore the message presented simultaneously to the other ('unattended') ear. The typical finding reported in many studies was that following the shadowing task, participants were unable to remember anything of the unattended message apart from its most basic physical characteristics. So, for example,

participants failed to notice (or at least to recall) changes to the language being spoken, but were often able to recall changes in the pitch of the speaker's voice (e.g., Cherry, 1953). Indeed, Moray (1959) reported that participants often failed to recognise words that had been repeated as many as 35 times in the unattended channel.

More recent studies have indicated that similar effects occur in more lifelike and dynamic settings as well. For example, Dalton and Fraenkel (2012) used binaural recording and presentation techniques in order to create a realistic three-dimensional auditory scene consisting of two conversations, one between two female voices and the other between two male voices. The participants were instructed to pay attention either to the female or the male conversation since they would receive questions about the content of the conversation afterwards. Without any warning, an additional male voice appeared in the scene and continuously repeated the phrase "I'm a gorilla" for 19 seconds as he walked through the scene. The sentence was chosen to create an auditory analogy of a visual experiment by Simons and Chabris (1999) whereby a person in a gorilla suit unexpectedly appeared in the scene (described in more detail later in this section). Strikingly, the majority of the participants who were instructed to attend to the female voices failed to notice the unexpected male voice (despite being able to detect it in a subsequent full attention control trial). Thus selective attention can operate at an early stage even under conditions that are more dynamic and naturalistic settings than those of the early dichotic listening studies.

In the light of such evidence, researchers have often been tempted to argue that attentional selection must occur at a relatively early stage of human information processing, such that unattended stimuli are rejected as soon as their simple physical characteristics (such as their location, frequency etc.) have been determined, and are

not subject to any significant further processing (e.g., see Broadbent, 1958). It should be noted, however, that the definition of a 'simple, physical characteristic' may not be as straightforward as it might at first seem (e.g., see Allport, 1992). For example, properties that are coded early in information processing in one sensory modality (such as location in vision) may only be derived much later in other sensory modalities (e.g., location is derived comparatively late in auditory processing; see Spence & Driver, 1994).

It is important to emphasise here that these demonstrations of 'early selection' assessed the extent of processing of the unattended information in terms of participants' subsequent memory for the content of the unattended stream. This approach was soon criticised, though, on the grounds that, by the time the participants were asked about the contents of the unattended stream, they may simply have forgotten the information, rather than never having perceived it in the first place (see Wolfe, 1999, for a discussion of this critical distinction between 'inattentional amnesia' and genuine 'inattentional blindness').

Nevertheless, the proposal that unattended stimuli were ruled out at a relatively early stage of human information processing has also been supported by subsequent studies that have examined the effectiveness of selective attention within the visual modality. At first, these visual studies drew inspiration from the auditory studies described above, and were therefore typically designed to create a more or less direct visual analogue of the dichotic listening task. For example, in one of the earliest studies of visual selective attention, reported by Neisser and Becklen (1975), participants were presented with two superimposed video streams, one showing two people playing a hand-slapping game and the other showing three people passing a basketball between one another. The participants in this study had to attend to one of the two video

streams in order to carry out a task on this attended information (such as counting the number of ball passes or hand slaps) while ignoring the other stream (in which unexpected events, such as the appearance of a new person carrying an umbrella, occasionally occurred). Just as had been found in previous auditory studies, the participants in Neisser and Becklen's study were unable to recall any of the unusual events in the unattended visual stream; this despite the fact that this stream had been presented from the same location as the attended stream.

However, one might argue that the failure to remember the unattended information in Neisser and Becklen's (1975) seminal study could reflect the fact that participants would have been focusing their overt attention on the attended stream and hence may have been making eye movements to keep track of the action that was occurring in that stream. Any such eye movements may simply have reduced the visibility of the unattended stream (due to retinal smearing). Note here that this criticism also applies to a number of the more recent demonstrations of inattention blindness, in which participants have typically been asked to carry out a task based on the events contained within a single video (in contrast to earlier studies involving superimposed videos). The striking finding to have emerged from this type of research is that participants can remain seemingly unaware of apparently salient visual events (e.g., the appearance of a person in a gorilla outfit) occurring in the same video as the primary visual task (e.g., counting the number of ball passes occurring in a basketball game; Simons & Chabris, 1999). However, because the unexpected visual event never completely coincides spatially with the attended events, these findings are also open to alternative explanations in terms of participants' eye movements.

Here, note that early studies of selective attention used auditory stimuli (at least in part) in an attempt to rule out potential alternative explanations of any attentional

effects obtained in terms of overt orienting involving eye movements. However, subsequent research has demonstrated that eye movements could, in fact, influence auditory attentional allocation during dichotic listening tasks (e.g., Hynd, Snow, & Willis, 1986; see also Gopher, 1973) so this assumption may not, after all, have been valid.

Nevertheless, results in favour of early selection have also been found in studies that have controlled for the potential influence of eye movements. For example, Rock and Gutman (1981) presented the participants in their study with pairs of superimposed outline drawings (either familiar or nonsense shapes) in different colours. The participants had to focus their attention on the line drawings that were presented in a particular colour (with the dummy task of rating the pleasantness of each drawing) while attempting to ignore the drawings presented in the other colour. In a subsequent surprise memory test, the participants were often unable to recognise any of the unattended shapes, even if the test occurred no more than a second after the presentation of the shape in question (see their Experiment 4). By contrast, participants' performance on a similar memory test for the attended shapes was fairly good. The use of static presentation in this experimental design helped to reduce the likelihood that eye movements played any role in determining the pattern of results obtained (an assertion that was confirmed by the monitoring of the eye position of a subset of the participants in Rock and Gutman's Experiment 1).

However, all of the above findings of 'early' visual selection (along with any such research that attempted to assess the processing of unattended information in terms of the participants' memories for that information) are open to the criticism, already mentioned in relation to the research on auditory selective attention, that the unattended information may have been perceived but then rapidly forgotten, rather

than not having been perceived at all (e.g., see Wolfe, 1999). Nevertheless, the development of brain imaging techniques has allowed researchers to assess the neural processing of unattended information more directly, thereby removing the need to rely on participants' memory for that information. The neuroimaging approach has also provided evidence in favour of early selection. For example, Rees, Russell, Frith, and Driver (1999) presented their participants with a series of pictures, each one superimposed with a string of letters (that formed a familiar word on certain trials but consisted of a meaningless string of letters on others). Note that the use of superimposed visual stimuli in this experimental design is similar to that of Rock and Gutman (1981) described above. In Rees et al.'s study, participants had to detect immediate stimulus repetitions, either in the picture stream, or else in the letter stream. When the participants attended to the stream of letter stimuli, the neural activity elicited by the words differed from that elicited by the non-words (i.e., the random letter strings). However, when the participants were attending to the pictures, the neural activity elicited by the words and non-words did not differ significantly. This result suggests that the unattended words were not even being processed up to the level at which they would have been differentiated from non-words, this despite the fact that the participants were looking directly at them (because they were presented at fixation). Thus, it would seem that unattended visual stimuli can be eliminated from processing at a relatively 'early' stage, at least under the particular experimental conditions used by Rees and his colleagues.

It should, however, be noted that a subsequent ERP study by Ruz, Worden, Tudela, and McCandliss (2005), based closely on the experimental design reported by Rees et al. (1999) in their fMRI study, found a somewhat different pattern of results.

Specifically, they observed that the patterns of ERP components elicited by words and

non-words differed significantly, even when the letter stimuli were not attended. This result would appear to suggest that unattended stimuli can be processed to a semantic (therefore relatively 'late') level after all. Given that the experimental designs used in these two studies were so similar, this difference in the pattern of results seems likely to be due to the differences in relative sensitivity of the fMRI and ERP techniques. Note, however, that Ruz et al. found that the nature of the word processing (as indicated by the differences in patterns of ERP components elicited by words and by non-words) was different in the unattended and attended conditions. Thus, even though Ruz et al.'s results suggest that the semantic processing of unattended stimuli can occur to some extent, they nevertheless suggest that unattended stimuli are processed differently (and presumably less thoroughly) than attended stimuli. The suggestion that unattended stimuli might, in fact, be processed to a semantic level of information processing is supported by a large amount of behavioural evidence, as described in the following section.

3. Behavioural Evidence for 'Late' Selection

Despite the above evidence in favour of 'early selection', behavioural research has also provided much evidence to suggest that supposedly 'unattended' stimuli can, in fact, be processed to a degree beyond that of the simple registration of their physical characteristics. As with the evidence for early selection, these observations began with research on the dichotic listening paradigm. For example, Moray (1959) reported that many of the participants in his now classic study remembered hearing their own name when it was presented unexpectedly in the unattended channel (along with some instructions that followed the name in that channel). By contrast, the participants could not remember those same unattended instructions if they were not preceded by

the participant's name (indeed, Moray demonstrated that participants could not even remember words that had actually been presented as many as 35 times in the unattended stream).

In addition, other researchers found that participants could often be influenced implicitly by the information being presented in the 'unattended' stream, even if they could not later recall it explicitly. For example, Mackay (1973) presented participants with ambiguous sentences to the attended ear (e.g., such as 'they threw stones toward the bank yesterday'), along with disambiguating information to the unattended ear (e.g., 'river' or 'money'). A subsequent memory test (based this time on recognition of the attended information) suggested that the participants had resolved the meaning of the ambiguous sentences in line with the information presented to the unattended ear, despite being unable to recall the content of this stream explicitly.

Meanwhile, Corteen and Dunn (1974, see also Corteen & Wood, 1972) reported an elegant study in which they demonstrated that people could process 'unattended' auditory stimuli up to the level at which semantic information became available, without any explicit awareness of having done so. In particular, they conditioned their participants to expect a small electric shock upon hearing a city name. Then, during dichotic listening, city names were presented to the unattended ear, with the additional instruction that participants should press a button every time they heard a city name.

Crucially, while less than 1% of the city names were explicitly detected by the participants, more than 30% of them elicited a galvanic skin response (GSR). The latter consistent with the sound of the city name triggering a small psychophysiological fear response, presumably linked with the expectation of the electric shock. This finding suggests that the information in the unattended ear had been processed up to a semantic level. Importantly, GSRs were even found for city

names that had not been presented during the training phase of the experiment, thus demonstrating that the 'unattended' names had been processed to a level at which semantic generalisation was possible. Based on findings such as these, 'late selection' theorists such as Deutsch and Deutsch (1963) proposed that information was processed to a semantic level before being filtered out of the processing stream. This proposal soon received support from studies of visual selective attention, as significant behavioural evidence emerged to suggest that, in many cases, 'unattended' visual stimuli could be processed to a deeper level than had at first been thought possible. For example, many studies now show that participants' responses can be primed by the semantic content of apparently-ignored visual stimuli. Tipper (1985), for instance, presented the participants in one of his studies with superimposed line drawings and asked them to attend to the drawing in one colour and to ignore the drawing presented in the other colour. The participants had to try and name the object represented by each of the attended pictures. Participants' responses to a particular attended stimulus were found to be affected by the identity of the stimulus presented on the immediately preceding trial, whether or not that previous stimulus had been attended. For example, the participants were able to name a picture of a dog more rapidly if they had named a dog (or a semantically related item, such as a cat) on the preceding trial than if they had previously named a neutral stimulus (such as a chair). This effect is often referred to as positive priming. In contrast, if participants had previously ignored a picture of a dog (or a semantically related item), they were slower in naming the picture of the dog on a subsequent trial (as compared with having previously ignored a neutral stimulus) – a result that is now commonly referred to as negative priming. Thus, even though participants were unable to recall the unattended stimuli explicitly (as shown on occasional catch trials in which they

were asked to report the unattended stimulus but frequently failed to do so), their performance was nevertheless influenced by these stimuli at a semantic level. This result would suggest that unattended visual stimuli can often be processed to a relatively advanced stage.

In fact, Tipper (1985) suggested that the relatively poor subsequent recall of the 'unattended' items in his study reflected the fact that the representation of these stimuli had been inhibited, following the relatively extensive processing necessary to produce priming effects (see also Tipper & Cranton, 1985; Tipper & Driver, 1988).

Tipper went on to suggest that this inhibitory process might have been responsible for people's failures to remember the unattended information when subsequently tested (e.g., as found in the early dichotic listening studies). This view would appear to support an account of the early selection findings in terms of inattentional amnesia (aided by the inhibition of unattended stimuli) rather than inattentional blindness.

Another very popular task developed by cognitive psychologists in the attempt to determine the extent to which irrelevant distractors are processed has become known as the flanker task (Eriksen & Eriksen, 1974). Participants in a typical study are asked to respond to a central target letter which is flanked by one or more distractor letters (which participants have to try and ignore). The distractor letters can be associated with responses that are congruent, incongruent, or neutral with respect to the target response. If the 'unattended' distractors received no processing whatsoever, one would expect there to be no difference in target responses (in terms of participants' speeded response latencies or accuracy) as a function of the type of distractor that has been presented. If, however, the distractors are processed to some extent, then target performance would be expected to be better on congruent trials and worse on incongruent trials, as compared with performance on neutral trials. Thus, cognitive

psychologists can infer the extent to which distractor stimuli are processed from the magnitude of any congruency effects observed in the target discrimination task (where congruency effects are usually calculated in terms of the impairment of performance seen on incongruent trials relative to that seen on the neutral or congruent trials). Eriksen and Eriksen's original study (along with many subsequent replications) demonstrated significant congruency effects due to the visual distractors. This implies that, at least under certain conditions, the distractors could be processed to the level at which responses are programmed despite being irrelevant to the task. The flanker paradigm has also been extended to the auditory modality. Chan, Merrifield, and Spence (2005) presented participants with 3 simultaneous voices, each saying a different word from a different spatial location. On each trial, the participants had to make a speeded discrimination response regarding the identity of the word spoken by the central speaker, while trying to ignore the distracting words being spoken by the speakers situated to either side of the central speaker (at spatial separations varying between 30 and 90 degrees). Just as shown previously in the visual modality, the participants responded significantly more slowly (and less accurately) on the incongruent trials than on the congruent distractor trials, thus showing interference by task-irrelevant distractors in the auditory modality. Generally-speaking, there has been much less research on selective attention within the tactile modality than there has been in either vision or audition. However, this area of research has begun to grow over the last few years and is now attracting considerable empirical interest (see Gallace & Spence, 2008, 2014; Johansen-Berg & Lloyd, 2000; Spence, 2002). This interest might in part be related to the real practical implications that are now emerging for the use of tactile warning signals in vehicles (see Meng & Spence, 2015, for a recent review) and in the area of tactile interface

design (e.g. Gallace, Tan, & Spence, 2007). For example, recent figures from a tactile technology company suggest that over three billion devices now contain their haptic technology (Business Wire, 2015). One line of research has established tactile analogues of the Eriksen flanker paradigm described previously. For example, Evans and Craig (1992) had their participants discriminate the direction of a moving tactile stimulus on one finger while ignoring a moving distractor presented to another finger. The participants responded more rapidly and more accurately when the direction of the distractor stimulus was congruent (vs. incongruent) with that of the target stimulus, suggesting that the tactile distractor was processed to a level at which it was able to influence responses, despite being clearly irrelevant to the task.

Subsequently, Soto-Faraco, Ronald, and Spence (2004) developed a tactile response competition paradigm using static (rather than moving) tactile stimuli. Participants had to discriminate the elevation of a series of continuous target vibrations (presented to either the top or bottom of a foam cube held in one hand) whilst trying to ignore pulsed distractor vibrations (presented to the other hand at an elevation that was either congruent or incongruent with that of the target stimulus). In line with the results of Evans and Craig's (1992) earlier study, Soto-Faraco et al. observed significantly better performance when the elevation of the vibrotactile distractor was congruent (vs. incongruent) with that of the tactile target, thus suggesting that the distractors were processed despite being entirely irrelevant to the participants' task (see also Driver & Grossenbacher, 1996; Gallace, Soto-Faraco, Dalton, Kreukniet, & Spence, 2008).

Note that although these distractor congruency effects were most pronounced when the target hand was unpredictable, the same pattern of results (although somewhat reduced in magnitude) was also found when the target hand was made predictable throughout a block of trials. Thus tactile distractors can interfere with the processing

of tactile targets, even when targets and distractors are made clearly distinguishable from one another spatially (thus allowing for the focusing of a participant's selective attention on the target hand). This might be taken as providing preliminary evidence that attentional selection within the tactile modality occurs relatively 'late' in information processing.

Indeed, subsequent research by Soto-Faraco et al. (2004) found that the magnitude of the tactile interference effect was modulated both by actual changes in the separation between the participant's hands (implying a role for proprioception in guiding selection) and by illusory changes in hand separation, induced by a mirror illusion (implying a role for visual information prior to tactile selection). This suggests that tactile selective attention was operating upon a representation of the tactile stimuli that was derived subsequent to the multisensory integration of tactile, proprioceptive and visual information. This finding supports the idea that tactile selection occurs relatively late in information processing (Gallace & Spence, 2014). However, it should be noted that little of the research on tactile selective attention has been designed specifically to address questions of early versus late selection. More research on this question might therefore be useful in the future.

Taken together, there is now a considerable body of evidence from research in audition, vision and touch to suggest that supposedly unattended information can in fact be processed beyond the level of the simple registration of its physical features. However, as was the case with the research taken to support early selection, these findings have been subject to several alternative interpretations. For example, one particularly important criticism relating to all of the experiments that have provided evidence in favour of late selection is that although participants are asked to ignore the irrelevant information (and presumably attempt to do as they have been

instructed!) they may nevertheless fail to ignore this information completely, despite their best intentions. Any observations of semantic processing of the ‘unattended’ information could therefore reflect failures in attentional focus, rather than necessarily indicating extensive processing of truly unattended material (e.g., Holender, 1986). Indeed, there is some evidence to suggest that, under certain conditions, the apparent processing of unattended information can be prevented when controls are taken to ensure that the unattended information remains genuinely unattended. For example, Lachter, Forster, and Ruthruff (2004) had their participants perform a lexical decision task in which they had to decide on each trial whether a target stimulus constituted a word or a non-word. Each target was preceded by a prime word, which was presented very briefly and then ‘masked’ (i.e., replaced by other visual stimuli, in order to ensure that no trace of the original visual stimulus remained). The prime word was either identical to the target word or else unrelated. Participants in this type of experiment are typically faster and more accurate on the lexical decision task when the target and prime are identical, as compared with when they are unrelated (an effect known as repetition priming).

However, Lachter et al. (2004) demonstrated that this effect could be eliminated if the participants were prevented from paying any attention to the prime stimuli (e.g., by presenting the primes at an unattended location and for a duration that was too short to allow a shift of attention to that location). In line with earlier results (e.g., Rees et al., 1999), this suggests that genuinely unattended words can be eliminated from information processing at a reasonably early stage. Indeed, Lachter et al. put forward a robust defence of Broadbent’s (1958) original model of early selection based on their data and on the argument (mentioned above) that all evidence in favour of late selection can actually be explained in terms of a process they term ‘slippage’, in

which attention is inadvertently paid to task-irrelevant items (see also Wood & Cowan, 1995a, b, for evidence to suggest that hearing one's own name in the unattended stream during dichotic listening might reflect the consequences of a temporary failure of selective attention, rather than the semantic processing of unattended information).

These findings have recently been extended to demonstrate no priming effect without spatial attention even for words that were presented with high frequency (Lien, Ruthruff, Kouchi, & Lachter, 2010). More importantly, the 'slippage account' has been generalised to the more common flanker paradigm (Gaspelin, Ruthruff, & Jung, 2014). Whereas flanker effects have traditionally been thought to reflect late selection, it was demonstrated that when 'slippage' was prevented by cueing the target location, flanker interference was diminished. These findings thus allow for a greater generalisation of Lachter et al.'s (2004) original findings to suggest that much of what has been viewed as evidence in favour of late selection could instead be explained in terms of 'slippage'.

4. Neural Mechanisms of Selective Attention

The behavioural evidence outlined in the previous two sections suggests that, under some circumstances, unattended information can be eliminated from information processing at a very early stage (see also Chun, Golomb, & Turk-Browne, 2011; Driver, 2001, for reviews). This idea has been supported by neuroscientific findings suggesting that spatial attention can modulate even the very early stages of neural information processing in the auditory, visual and tactile modalities.

One important advantage of the cognitive neuroscientific approach (as compared to the traditional cognitive psychological approach described earlier) is that it has

allowed researchers to examine whether the activation of specific brain areas at identifiable points in particular hierarchies of information processing can be modulated by attention. This approach might therefore appear to be able to provide more concrete definitions of ‘early’ and ‘late’ selection effects than those provided by the traditional cognitive approach. (Note that here we take the traditional cognitive approach to be one based on behavioural research and box-and-arrow models of the mind, in which attention was viewed as a unitary system that would operate at specific stages within the hierarchy of information processing; see Allport, 1992, for a discussion of some of the problems faced by traditional cognitive researchers in this regard). Indeed, the fact that the notion that information passes sequentially through strict neural processing hierarchies has little support these days. For example, it is now generally agreed that visual information processing involves feedback (or ‘recurrent’) processing, in which ‘later’ areas feed information back to ‘earlier’ areas (e.g. Lamme, Super, & Spekreijse, 1998). Indeed, some researchers argue that such recurrent processing is essential for visual awareness (see Lamme, 2003, for a review; see also Gallace & Spence, 2014). In addition, there is reliable evidence to suggest that different aspects of incoming information can be processed in parallel by the brain, as demonstrated in vision (e.g. see Goodale & Milner, 1992, for a review of evidence supporting the existence of two parallel processing streams – known as the ‘ventral’ and ‘dorsal’ streams – in the neural processing of visual information), in hearing (e.g. see Alain, Arnott, Hevenor, Graham, & Grady, 2001; Rauschecker & Tian, 2000, for suggestions that a similar distinction may also apply to the processing of auditory stimuli) and in touch (e.g. see Pons, Garraghty, & Mishkin, 1992, for early work on the possible parallel processing of different aspects of tactile information; see Spence, 2013, for a multisensory take on the two stream approach).

Nevertheless, the mounting evidence that even primary sensory areas (through which it is agreed that all incoming information from that particular sensory modality must pass) can be subject to attentional modulation is often taken to support an early selection view. In addition, researchers have sought to demonstrate that attentional modulations can occur soon after stimulus onset, thus providing a definition of ‘early’ selection in terms of processing time rather than brain region. Below we discuss the evidence for attentional modulations of visual, auditory and tactile information processing, at stages that are defined as ‘early’ either in terms of brain area, or in terms of processing time, or both. We then examine the contribution that these findings have made to the question of the extent to which unattended information is processed. Note that our discussion here is focused on the neural mechanisms of spatially-selective attention (rather than attention to other, non-spatial stimulus attributes) simply because this is the area in which the majority of the research has been carried out.

4.1 Audition

There is now considerable evidence to suggest that spatial attention can affect the early stages of auditory information processing (see Fritz, Elhilali, David, & Shamma, 2007; Giard, Fort, Mouchetant-Rostaing, & Pernier, 2000, for reviews). One fruitful line of research has used event-related potential (ERP) recording to assess neural processing of auditory information. In a typical design, participants attend to auditory stimuli presented at a particular location while attempting to ignore task-irrelevant stimuli at another spatial location. ERPs elicited by stimuli presented at the attended location are then compared with the ERPs elicited by the same stimuli when that location is ‘unattended’. Although there is no physical difference between the stimuli,

they typically elicit different ERP patterns even at relatively short latencies after stimulus presentation, thus suggesting that auditory selective attention can have an important effect even on early perceptual processes. Specifically, the amplitudes of certain early, sensory-related ERP components elicited by attended stimuli have been shown to be greater than those elicited by unattended stimuli, with these differences starting as early as 60 to 80 ms after stimulus onset (e.g. Hansen & Hillyard, 1983; Hillyard, Hink, Schwent, & Picton, 1973; Näätänen, Gaillard, & Mäntysalo, 1978). There is now even some evidence to suggest that under certain conditions, these differences can occur as early as 20 to 50 ms after stimulus presentation (e.g., Hoormann, Falkenstein, & Hohnsbein, 2000). The aforementioned studies all used rudimentary auditory stimuli such as simple tones. However, an increasing body of research now shows signs of early selection on more complex speech stimuli (e.g. Ding & Simon, 2012; Kerlin, Shahin, & Miller, 2010; O'Sullivan, Power, Mesgarani, et al., 2015; Power, Foxe, Forde, Reilly, & Lalor, 2012; Zion Golumbic, Ding, Bickel, et al., 2013). For example, Kerlin et al. (2010) used a more traditional cocktail party paradigm in which the participants were presented with either one sentence to one ear or two sentences, one to either ear. They were cued beforehand which ear to attend to and the task was to report whether the delayed word following an incomplete sentence was semantically congruent or incongruent. Concurrently recorded EEG revealed an early attentional gain towards the attended side, which was evident through greater suppression of alpha frequency band in the EEG on the opposite hemisphere to the attended ear compared with alpha on the same hemisphere. Because low alpha amplitude is often coupled with enhanced processing (e.g. Palva & Palva, 2007), these findings thus converge with the ERP studies in suggesting that attention can selectively operate early on in perceptual processing. However, Power et al. (2012)

reported conflicting evidence from their dichotic listening paradigm, which only showed an attentional modulation around 200 ms after stimulus presentation. They suggested that this modulation might reflect the suppression of irrelevant information at a post perceptual stage. These findings converge with a recent report of late attentional selection (200-250 ms post stimulus onset) using a similar task set-up (O'Sullivan et al., 2015). The inconsistencies concerning the stage of processing at which attention first appears to be operating could be due to differences in the complexity of the stimuli used (e.g. very simple auditory stimuli presented in isolation versus speech in cluttered environments). However, it is also likely that attentional processes occur at several stages, sharpening selectivity of relevant stimuli at the expense of irrelevant information (e.g. Teder-Sälejärvi & Hillyard, 1998; Zion Golumbic et al., 2013). This has for example been demonstrated in a cocktail party setting (Zion Golumbic et al., 2013), whereby two separate neuronal mechanisms in response to the attended channel were identified, operating at different stages of information processing. While one is mainly confined around auditory cortex, reflecting enhancement of the attended channel (although the unattended channel also is represented at this point), the other mechanism is more widely distributed and involves higher-level areas, tuning the attended speech only as it unfolds. Neuroimaging studies of spatially-selective auditory attention have also demonstrated that paying attention toward the location of auditory stimuli (as compared with ignoring those very same stimuli) can activate areas of primary auditory cortex as well as temporal lobe auditory association areas (e.g., Alho, Medvedev, Pakhomov, et al., 1999; O'Leary, Andreasen, Hurtig, et al., 1997). In line with the ERP research described above, this research implies that selective attention can have effects on relatively early stages of auditory information processing.

This assertion is further strengthened by studies that have used single cell recording techniques in non-human primates. Researchers working in this area have been able to measure the responses of individual neurons while an animal performs a particular task. This type of research has also demonstrated an attentional modulation of neuronal responses in auditory cortex (e.g. Benson & Hienz, 1978). Thus, overall, the neuroscientific research appears to agree that attentional modulations can occur very soon after stimulus onset and in brain areas that are involved in the early processing of auditory information.

4.2. Vision

There is also a consensus in the neuroscience community that spatial attention can modulate the early stages of visual information processing. For example, O'Connor, Fukui, Pinsk, and Kastner (2002) carried out an fMRI study in which the participants either had to attend to a checkerboard stimulus or else attend to the other side of the screen (while the checkerboard remained present, but was relatively unattended). Activity levels in 'visual cortex' (pooled in this case across several early visual processing areas, including primary visual cortex) were found to be higher in the attended condition than in the unattended condition. This result has been replicated frequently throughout the literature (see Kastner, 2004, for a review). However, O'Connor et al. extended previous findings by demonstrating that this attentional modulation effect could also be found in the lateral geniculate nucleus of the thalamus: a brain area that is known to be involved in the very early processing of visual information.

The finding that spatial attention can modulate brain areas that are involved in the early processing of visual information has been accompanied by findings of

attentional modulations of certain visual ERP components soon after stimulus onset (for reviews, see Hillyard, Vogel, & Luck, 1998; Mangun, 1995). Several studies have also combined brain imaging with ERP recording in order to exploit the high temporal resolution of ERP techniques as well as the relatively high spatial resolution of PET or fMRI. For example, Heinze, Mangun, Burchert, et al. (1994) used PET and ERP recording in order to demonstrate an attentional modulation of responses in certain areas of visual cortex within 80-130 ms of stimulus onset.

Similar findings have also emerged from studies of attentional function at the neuronal level using single cell recording techniques in non-human primates. In fact, there is now reliable evidence to suggest that spatial attention can modulate the responses of individual neurons throughout the macaque visual system (e.g., see Treue, 2001, for a review). However, findings relating to the issue of whether or not neural responses in primary visual cortex (V1) are subject to attentional modulation have, until fairly recently, been rather mixed (see Posner & Gilbert, 1999, for a review). For example, Moran and Desimone (1985) and Luck, Chelazzi, Hillyard, and Desimone (1997) both failed to find any attentional modulation of the activity of V1 neurons, despite finding clear evidence for attentional effects occurring in other early visual areas (e.g., in V2 and V4). Nevertheless, there is now an increasing body of evidence that V1 neurons can be subject to attentional modulation, at least under certain conditions (see Treue, 2001, for a review). For example, Roelfsema, Lamme, and Spekreijse (1998) devised a task in which their monkeys had to fixate a dot, which was then joined to one of two curves, each leading to another dot. The monkey's task was to make an eye movement to the dot that was joined by the curve originating from the fixation dot. Using this task, a curve passing through a particular area of the visual field could either be made a target (by connecting it to the fixation

dot) or a distractor (by not connecting it). Thus, the same cell's receptive field (RF) could fall on the target curve in one trial and on the distractor curve in another trial. Recordings were taken from 45 neurons in the primary visual cortex of two monkeys. Overall, firing rates were higher when the RF fell on a target curve than when it fell on a distractor curve, indicating that neuronal responses in primary visual cortex could be modulated by the attentional demands of the monkey's task.

Given the variability of the results concerning the attentional modulation of V1, it is perhaps not so surprising that studies that have looked at the possible attentional modulation of LGN neurons have also reported mixed results. Although there is some limited evidence to suggest that the activity of neurons within the LGN can be modulated by attention (e.g., Vanduffel, Tootell, & Orban, 2000), the few single-cell recording studies in this area have usually failed to find attentional effects at this very early level of information processing (e.g., Bender & Youakim, 2001; Mehta, Ulbert, & Schroeder, 2000). Nevertheless, taken together, the findings from visual neuroscience studies in both human and non-human primates appear to agree that the attentional modulation of neural processing can occur in brain areas involved in the early stages of visual information processing and within around 100 ms of stimulus onset.

4.3 Touch

Just as we have seen to be the case for both audition and vision, the neuroscientific evidence also suggests that attention can affect the early stages of the neural processing of tactile information (see Gallace & Spence, 2014; Johansen-Berg & Lloyd, 2000, for reviews). For example, researchers have demonstrated attentional modulations of ERP components relating to tactile perception as early as 80ms after

the onset of a tactile stimulus (e.g., Eimer & Forster, 2003).

Similarly, attentional effects in primary somatosensory cortex (S1) have been demonstrated in humans using fMRI (e.g., Johansen-Berg, Christensen, Woolrich, & Matthews, 2000) and PET (e.g., Meyer, Ferguson, Zatorre, et al., 1991). Note, however, that these results might depend on the exact parameters of the experimental design used, as other studies have failed to demonstrate clear attentional effects on activity in S1 (e.g. Burton, Abend, MacLeod et al., 1999; Burton, Sinclair, & McLaren, 2008; Mima, Nagamine, Nakamura, & Shibasaki, 1998), although these studies have nevertheless often demonstrated attentional modulation of other (later) somatosensory areas (e.g. S2; see Gallace & Spence, 2014).

This overall pattern of results is supported by a small number of single-cell recording studies that have demonstrated a significant attentional modulation of neuronal responses in primary somatosensory cortex (e.g. Hsiao, O'Shaughnessy, & Johnson, 1993; Hyvarinen, Poranen, & Jokinen, 1980). Thus, although there has been less research on the neural mechanisms of tactile selective attention than there has been on the mechanisms of visual and auditory attention, the available research appears to agree that attention can modulate the early stages of tactile information processing.

4.4 Implications for the 'Early' versus 'Late' Debate

Overall, there is a significant body of evidence to suggest that attentional modulation of visual, auditory and tactile information can occur in brain areas involved with early information processing and at times very soon after stimulus onset (see also Driver & Frackowiak, 2001, for a review). However, the fact that the brain differentiates between attended and unattended inputs at an early stage of processing does not necessarily mean that unattended information is ruled out of processing altogether at

that stage. Instead, these results simply demonstrate that attended and unattended stimuli are differentiated from this stage of processing onwards. In fact, most of the studies described above demonstrated an attenuated response to unattended stimuli, rather than no response at all. Nevertheless, the research might suggest that unattended stimuli become less and less well-represented as processing proceeds. For example, the extent to which attention can modulate neuronal activity has been seen to increase throughout the visual system. Specifically, the attentional modulations of activity in V1 are typically smaller in magnitude than those elicited by the same experimental manipulation to activity in a ‘higher’ visual area such as, for example, V4 (e.g., Kastner, De Weerd, Desimone, & Ungerleider, 1998; Martinez, Anllo-Vento, Sereno, et al., 1999; Mehta, Ulbert, & Schroeder, 2000; O’Connor et al., 2002; see also Vibell, Klinge, Zampini, Spence, & Nobre, 2007). This is also evident in the auditory modality, where spatial attention can appear to influence processing at different stages (e.g. Teder-Sälejärvi & Hillyard, 1998; Zion Golumbic et al., 2013). Recall that the research looking at possible attentional modulations of the neural processing of tactile information also found more reliable modulations in secondary somatosensory cortex than in primary somatosensory cortex (e.g., Mima et al., 1998; see Gallace & Spence, 2014, for a review). Such results might be taken to suggest that the neural representation of unattended stimuli is gradually reduced as processing progresses, rather than unattended stimuli necessarily being completely eliminated at one fixed point in information processing.

This suggestion certainly fits with the ‘biased competition’ model of visual selective attention that was put forward by Desimone and Duncan (1995, see Duncan, 2006, for a review). According to this model, neuronal activity can be biased in favour of those neurons that respond to a particular attended stimulus. This initial prioritisation of

selected neurons gives them an advantage in their subsequent interactions with neurons that are not preferentially activated (because they do not respond to the attended stimulus). Thus, according to this model, unattended information would not be ruled out of processing at a particular point, but would instead be subject to a continued bias against it throughout processing. This intermediate position is echoed in recent proposals for a resolution to the 'early versus late' selection debate, as outlined below.

5. Possible Resolutions to the Debate

The studies reviewed so far all agree that, at some stage, attended information is processed with a higher priority than is unattended information. However many of these studies differ in their estimates of the effects that this process of prioritisation might have on the level to which the unattended information is processed. In contrast to the extreme positions espoused by the 'early' (e.g., Broadbent, 1958) and 'late' selection theorists (e.g., Deutsch & Deutsch, 1963), several researchers noted the variability of the findings and proposed compromise positions (see Shulman, 1990, for a discussion of the dangers of failing to acknowledge the extent of the variability of the results in this research area). For example, Treisman (e.g. 1960) proposed that unattended information was attenuated early in processing, rather than being filtered out completely. Her model accommodated the findings concerning the limited processing of unattended stimuli, but also allowed for the possibility of further processing of this information if it were sufficiently salient. According to the model, such information would be able to reach consciousness despite having been attenuated, because the thresholds for activating salient information were lower than for other information. This proposal of variable thresholds for triggering the

processing of incoming information allowed for different participants to have different threshold levels for different types of information. Treisman's model was therefore capable of accounting for the observations of individual differences in the efficiency of selective attention as described earlier (recall, for example, that Moray, 1959, found that, although a subset of his participants noticed their own names when they were presented in the unattended ear, a significant number of participants did not). However, whereas these ideas relate mainly to the nature of the irrelevant information, subsequent research has indicated that the nature of the relevant information can also play a part in determining the amount of processing that unattended stimuli receive.

Lavie (1995) reinvigorated the early/late selection debate by putting forward the suggestion that selection could occur either early or late in human information processing, depending on the perceptual load of the relevant task (i.e., the demands placed on the perceptual system by that task; see Johnston & Heinz, 1978, for an earlier hybrid model of selection). Lavie argued that the perceptual system has a limited capacity, but that all stimuli are automatically processed unless that capacity is exceeded. According to this view, selection can only occur at an 'early' stage of information processing if the relevant task uses up all of the available processing capacity (i.e., under conditions of high perceptual load). If the perceptual load of the task is insufficient to exhaust processing capacity, then distractors will be processed automatically and selection will be seen to occur at a 'later' stage of information processing.

In order to provide a direct test of her theory, Lavie (1995) assessed the performance of participants on a response competition task similar to that designed by Eriksen and Eriksen (1974; and described in Section 3). Distractor interference was measured in

terms of distractor congruency effects (in which responses are typically shown to be slower when distractors are associated with responses that are incongruent (vs. congruent) with the target response). Lavie also manipulated the demands of the target task, such that the perceptual load was either high (e.g., searching for an N among several other letters) or low (e.g., searching for an N amongst Os). Lavie reported that the participants were able to ignore the distractors more effectively (implying ‘early selection’) under conditions of high perceptual load than under conditions of low perceptual load (implying ‘later’ selection in this case).

The idea that the stage of processing at which selection occurs can vary depending on the perceptual load of the relevant task has now been supported by numerous studies in a wide range of settings, using both behavioural and neurological measures (see Lavie, 2000, 2005, 2010, for reviews). For example, Rees, Frith and Lavie (1997) carried out an fMRI study in which the participants viewed a peripheral display of moving dots which was irrelevant to a word-based task presented at fixation. Neural activity in motion areas MT/MST was reduced when the word-based task was highly demanding (i.e. identifying words containing two syllables) as compared to when it was less demanding (i.e. identifying words written in upper case letters vs. in lowercase). This result suggests, in line with perceptual load theory, that the neural processing of the irrelevant information was modulated by the perceptual demands of the relevant task. Similar effects have now been shown as early in visual processing as the LGN (e.g. O’Connor et al., 2002, as discussed earlier).

Recent studies have also provided direct evidence for a role of perceptual load in determining awareness, in contrast to the more indirect measures described so far, such as RTs or of brain activity. For example, Cartwright-Finch and Lavie (2007) used an inattention blindness paradigm (see Section 2) whereby participants were

presented with a cross and either judged which of the arms was blue (vs. green; low perceptual load) or which of the arms was longer (high perceptual load). Note that with this manipulation, the visual display was identical for both low and high perceptual load and the only difference between the conditions was the level of processing capacity needed to identify the target (simple colour discrimination versus subtle difference in length between the two arms). On the final trial, a small square appeared simultaneously with the cross in the periphery, and participants were asked immediately afterwards whether they had noticed anything else other than the target display. The results demonstrated an increase in inattention blindness as a function of perceptual load such that fewer people noticed the unexpected event whilst performing a task of high (vs. low) perceptual load.

A similar yet perhaps more striking finding was recently reported by Calvillo and Jackson (2014) who unexpectedly presented their participants with either an image of an animal or an inanimate object on the final trial concurrent with a low or high perceptual load task. Animate stimuli are thought to be processed more quickly than inanimate (e.g. New, Cosmides, & Tooby, 2007) so typically detection of an unexpected stimulus would be higher if it was animate compared with inanimate. Indeed, this was demonstrated under conditions of low load. However, detection overall under high load was significantly reduced, and importantly, the difference between animate and inanimate detection was abolished, thus suggesting that basic categorization of an irrelevant object can be lost when the relevant task exhausts all processing resources.

However, the reliance of the inattention paradigm on retrospective questioning leaves open the possibility that failures to report the unexpected stimulus reflect failures of memory rather than lack of perception. To avoid such ambiguity, Macdonald and

Lavie (2008) conducted a range of experiments whereby a critical stimulus (CS) appeared repeatedly in the periphery of the target display of a traditional high or low load visual search task. The participants were informed beforehand about the potential appearance of the CS and were asked to respond whenever they detected it. Similarly to Cartwright-Finch and Lavie, Macdonald and Lavie demonstrated a reduction in detection sensitivity for the CS under high perceptual load compared with low perceptual load, providing further evidence that perceptual load can determine people's awareness, even of expected stimuli. Taken together, these findings suggest that the level of perceptual load does indeed determine conscious perception of additional information, depending on whether selection occurs early (as in the case of high perceptual load) or late (low perceptual load).

Recent evidence also suggests that perceptual load can modulate the extent to which unconscious processing occurs. For example, Bahrami, Carmel, Walsh, Rees, and Lavie (2008) assessed participants' processing of gratings presented in the periphery which were either tilted to the left or the right whilst they were performing either high or low perceptual load visual task at fixation. The peripheral stimulus was made 'invisible' by presenting it monocularly and masking it with a simultaneously flashing mask to the other eye. Whereas orientation adaptation was evident under low perceptual load, suggesting that the invisible gratings had been processed, any adaptation was eliminated under high perceptual load. This finding suggests that the level of perceptual load in the relevant task can even modulate the unconscious processing of invisible information.

Given the wide range of experimental evidence now supporting perceptual load theory, it has often been considered to have provided something of a resolution to the long-running 'early/late' selection debate. However, some of the principles of

perceptual load theory have been challenged in recent years. One aspect difficult to reconcile is that, as yet, no independent measure of perceptual load has been provided. Instead, researchers have had to rely on operational definitions, based on observations that a given manipulation of perceptual load ‘worked’ in a given experimental setting (which raises particular problems when trying to interpret the results of studies where a manipulation of perceptual load is found to have no effect on distractor processing). In addition, some researchers have started to propose explanations other than perceptual load to account for the reduction in distractor processing typically seen under high (vs. low) perceptual load. For example, Benoni and Tsal (2010, 2012, 2013; Tsal & Benoni, 2010; see also Wilson, Muroi, & MacLeod, 2011, for a similar account) have offered an alternative late selection proposal, arguing that low-level effects of visual dilution can explain the reduction in distractor processing that typically occurs when nontarget items are added to a visual display. In other words, they argue that irrelevant information is processed to the same extent regardless of perceptual load, but that, in the typical high load visual search displays, the nontargets compete with the distractor for neuronal representation in the visual system, which results in dilution of this representation. Even though the dilution proposal provides a plausible explanation for some of the findings concerning perceptual load, it can only account for findings from one type of load manipulation in which the number of items in the relevant display varies. For example, it cannot explain set-ups that use identical stimuli under low and high load but different task instructions, such as judging the colour versus length of the arms of a cross (Cartwright-Finch & Lavie, 2007), or attending to a feature (low load) versus the conjunction of two features (high load; Lavie, 1995). It also fails to explain how for example the level of perceptual load in a visual task can modulate the extent to which mind wandering

occurs, given that this type of distraction is not even visual but internally generated (Forster & Lavie, 2009). Thus, overall, the dilution account, while offering a plausible explanation for some of the findings usually attributed to perceptual load effects, appears too restricted to offer a full alternative to perceptual load theory and the wide range of findings that it can explain.

However, Scalf, Torralbo, Tapia, and Beck (2013) have recently proposed an alternative account, which they claim can explain both the dilution and perceptual load accounts. Their proposal is largely based on the previously-mentioned model of 'biased competition' (Desimone & Duncan, 1995), with the central claim that our limited perceptual capacity manifests itself in low-level competition in the visual cortex. It thus follows that the reduction in distractor processing seen under typical high load displays occurs because they usually involve increases in either the number of non-targets or in the similarity between targets and non-targets, both of which would lead to a greater level of competition between targets and non-targets. This increased competition then reduces the neuronal representation of the target, creating the need for a top-down bias in favour of the relevant stimuli in order to resolve the competition between the target and non-targets. This then leads to the distractor being excluded from processing. One clear advantage of this account is that it relates clearly to well-understood neural mechanisms. However, it does fail to account for findings such as that perceptual load can also determine awareness of a stimulus when stimuli are presented in succession and hence no simultaneous competition is evident (Carmel, Thorne, Rees, & Lavie, 2011).

More recently, both the perceptual load and dilution accounts have been challenged by findings mentioned in Section 3. Gaspelin et al. (2014) not only demonstrated that flanker interference can be eliminated when 'slippage' is prevented (by either

presenting a cue determining target location or making the target salient by presenting it in colour whilst the nontargets and the flanked distractor were presented in white). They also demonstrated that this pattern of flanker elimination was present under conditions of low perceptual load. On the other hand, when no cue was present, a typical increase in distractor interference was seen in the low load condition compared with high load. This finding is problematic for both perceptual load theory and the dilution account because in conditions of either low perceptual load or low visual interference, flanker interference effects should be seen. However, further research is needed to investigate whether 'slippage' can unequivocally explain the extent to which distractor processing occurs, or whether it is specifically confined to flanker interference.

Another possible limitation of the research that has been conducted in this area so far is that it has concentrated almost exclusively on perceptual load within the visual modality. There have been a handful of attempts to investigate whether the principles of perceptual load would also hold in the auditory modality as well. These have resulted in mixed findings. For example, Alain and Izenberg (2003) demonstrated that ERP components elicited by deviant (yet task-irrelevant) auditory stimuli can be reduced under a high (vs. low) perceptual load in a relevant auditory task), in line with perceptual load theory. Furthermore, Francis (2010) reported a perceptual load modulation using a task which consisted of two spoken words ("bead" or "bad"), presented simultaneously. Participants attended to one voice (defined by gender) whilst ignoring the other voice and reported the word when a concurrent tone was of a specific identity. Under low load, participants focused on the pitch of the tone, and under high load a conjunction of pitch and whether the tone was amplitude-modulated or not. There was some suggestion of a reduction in distractor interference under high

as compared with low perceptual load, but the interaction between level of perceptual load and distractor congruency was not statistically significant, meaning that these findings should be treated as no more than preliminary. More recently, Fairnie, Moore, and Remington (2016) asked participants to identify a target sound (lion's roar or a dog's bark) presented amongst other animal sounds. Perceptual load was manipulated by varying the number of concurrent nontarget sounds. A critical stimulus (CS; sound of a car) was presented simultaneously on 50% of the trials and participants indicated whenever they detected its presence. The results demonstrated a decrease in CS detection with an increase in auditory perceptual load.

However, some studies have failed to find the predicted effects of perceptual load in the auditory domain. For example, Gomes, Barrett, Duff, Barnhardt, and Ritter (2008) reported no difference in ERP measures of processing of a relevant versus irrelevant auditory channel as a function of perceptual load. In line with this, Murphy, Fraenkel, and Dalton (2013) reported a failure to find any modulation of auditory perceptual load on auditory distractor processing using two different manipulations of perceptual load and two different measures of distractor processing. First, they used an auditory flanker task which consisted of a sequence of six spoken letters, centrally presented in a female voice. The task was simply to identify the target letter (P or T). Under low load, the five non-target letters were all X's, whereas under high load the non-targets were similar sounding letters. A distractor letter (also P or T) spoken in a male voice was presented at the midpoint of the sequence, at a peripheral spatial location either to the left or the right of centre. In contrast to the predictions of perceptual load theory, distractor interference was equal under high and low perceptual load, even though there was clear evidence for a successful load manipulation (slower RTs under high vs. low load). Second, Murphy et al. used the inattention paradigm to assess whether

the detection of an unexpected auditory event would be modulated by the level of auditory perceptual load in a primary task. Participants discriminated the duration (low load) or the duration and frequency (high load) of a tone presented in one ear, and on the final trial, a spoken word was presented in the unattended ear. Similarly to the flanker results, there was no difference in detection of the unexpected word as a function of auditory perceptual load. Overall, the authors concluded that the auditory modality might be less open than the visual modality to modulations by perceptual load, perhaps because of the differences with which perceptual demands are handled in vision and audition. Whereas vision has strong mechanisms for spatial selection of relevant portions of the perceptual input, the auditory system does not have an equivalently strong means of focusing perceptual capacity. For this reason, Murphy et al. argued that full capacity is unlikely to be solely allocated to task-relevant stimuli, even in those situations where the task at hand is perceptually demanding. This idea fits in with the suggestion that hearing acts as an early warning system (e.g. Dalton & Lavie, 2004) because of its capacity to monitor the environment in all directions in contrast to the more restricted focus of the other sensory modalities.

In the tactile domain, to our knowledge there is so far only one reported investigation into whether the principles of perceptual load theory apply. Adler, Giabbiconi, and Müller (2009) reported two experiments in which the participants either had to detect (low perceptual load) or discriminate (high perceptual load) a target in a stream of tactile stimuli presented to one hand while ignoring tactile distractors presented to the other hand. ERPs revealed greater processing of irrelevant compared to relevant information, thus suggesting that the distractors on the unattended hand captured attention. However, this pattern of results was only evident in the low load experiment, with processing of irrelevant versus relevant information significantly

reduced in the high load experiment. These findings thus suggest that increased demands in a focal tactile task can reduce processing of irrelevant tactile distractors, providing preliminary evidence for a similar role of perceptual load in touch as in vision. However, these findings need to be replicated before any firm claims that perceptual load extends to the tactile domain can be made.

Despite the underrepresentation of unisensory studies of perceptual load effects in audition and touch, there have been a number of recent studies that have investigated the possible existence of crossmodal perceptual load effects. One advantage of this line of investigation is that it might provide a test of whether the ‘limited perceptual capacity’ described within the perceptual load theory is modality-specific (cf. Wickens, 1984, 1992) or whether instead it consists of a common pool of processing resources that is shared between the different sensory modalities. These questions are important given a high level of variability in the literature on the question of whether or not attentional resources are shared between the different sensory modalities (e.g. see Arnell, 2006; Martin, 1980; Soto-Faraco, Spence, Fairbank, et al., 2002; Spence, Nicholls, & Driver, 2001; Treisman & Davies, 1973, for successful demonstrations of crossmodal competition for attention, but see Alais, Morrone, & Burr, 2006; Duncan et al., 1997; Soto-Faraco & Spence, 2002; Wahn & König, 2016, for a failure to find any such crossmodal competition under slightly different experimental conditions). There was initially some variability in the results of research on the possibility of crossmodal perceptual load effects, with some studies failing to find reliable demonstrations of such effects (e.g. Rees, Frith, & Lavie, 2001; Tellinghuisen & Nowak, 2003), while others found some suggestion of crossmodal effects (e.g. Berman & Colby, 2002; Houghton, Macken, & Jones, 2003; Otten, Alain, & Picton, 2000; Parks, Hilimire, & Corballis, 2009). However, recent investigations using

inattention paradigms with a focal visual task have provided more consistent results (although see Sandhu & Dyson, 2015, for a recent failure to find any crossmodal perceptual load effects for both visual and auditory focal tasks). For example, Macdonald and Lavie (2011) used the same visual task as Cartwright-Finch and Lavie (2007), whereby participants either judged which arm of a cross was blue (low load) or which arm was longer (high load). On the final trial, a pure tone was presented simultaneously with the visual display. A greater proportion of participants in the high perceptual load condition failed to report the occurrence of the sound (when asked immediately afterwards) compared with participants in the low perceptual load condition, suggesting that the perceptual demands of the visual task determined auditory awareness.

These findings have also been replicated with a detection sensitivity paradigm (Raveh & Lavie, 2015), demonstrating a reduction in the ability to detect a frequently occurring tone when the main task is of high (vs. low) perceptual load. Although these behavioural findings are in line with the predictions of perceptual load theory, they cannot speak to the question of whether the increased inattention under high load reflects a reduction in perception or suppression of post-perceptual processing.

However, Molloy, Griffiths, Chait, and Lavie (2015) used the same paradigm as Raveh and Lavie whilst recording MEG. While activation in response to the appearance of the tone was evident in the auditory cortex under conditions of low visual load, there was a significant reduction seen under high visual load. Importantly, this difference in early auditory processing was coupled with a difference in amplitude of later activity, which is often associated with awareness. Thus, these findings altogether suggest that capacity is to some extent shared between the visual and auditory domains, such that the perceptual load of a visual task can modulate

perception of auditory stimuli.

The latest evidence suggests that vision and touch might also share processing capacity in this way. Murphy and Dalton (2016) used the same visual task as Macdonald and Lavie (2008) and Raveh and Lavie (2015), presenting a brief vibration to the palm of participants' left or right hand on 50% of the trials. Similarly to previous studies, detection sensitivity to the vibration was significantly reduced when the concurrent visual task was of high versus low load, suggesting that visual perceptual load modulates awareness of task-irrelevant tactile information. These findings converge with a previous experiment demonstrating a reduction in detection of change to a pattern of simultaneous vibrations under dual (vs. single) task conditions. Specifically, the reduction was evident when participants performed a concurrent task of either verbally reporting the spatial location of a light or making a movement towards this location compared with responding to the tactile task on its own (Gallace, Zeeden, Röder, & Spence, 2010). It remains to be determined whether tactile perceptual load can equally modulate visual or auditory awareness.

The variation in the results of the studies of crossmodal perceptual load might be related to the lack of an independent measure of the extent of the load imposed on the perceptual system by a particular task. It could, for example, be argued that any failures to demonstrate significant crossmodal perceptual load effects may have been due to the studies in question simply using too weak a manipulation of perceptual load. For example, the auditory discrimination of the number of syllables (used in Rees et al.'s, 2001, crossmodal study) is likely to have been much easier than the discrimination of the number of syllables in words presented visually (used in their successful intramodal study of perceptual load in vision; Rees et al., 1997).

Furthermore, it is worth noting that studies demonstrating a crossmodal load effect

tend to use a visual focal task (e.g. Macdonald & Lavie, 2011; Murphy & Dalton, 2016; Otten et al., 2000; Raveh & Lavie, 2015), raising the possibility that the modality of the main task might also account for the variation in the results.

Earlier, we outlined how the neuroscientific evidence appears to support a compromise position, suggesting that unattended stimuli might be gradually filtered out throughout information processing, rather than being completely eliminated from processing at one fixed point in the system. This suggestion from neuroscience, along with the behavioural evidence that unattended information receives more or less processing depending on the specific perceptual demands of the attended task (e.g. Lavie, 1995), would appear to agree that there is no fixed point at which unattended information is excluded from processing, but rather that the prioritisation of processing is flexible, depending on the salience of the stimuli involved, the particular demands of the task at hand, and the current goals of the observer.

6. Working Memory and the Locus of Selection

There is also evidence to suggest that the extent to which unattended information is processed can vary from participant to participant. Recall, for example, that only one in three of Moray's (1959) participants noticed their own names being presented in the unattended stream. There is now evidence to suggest that this inter-participant variability might be related to individual differences in working memory capacity. For example, Conway, Cowan and Bunting (2001) have shown that participants with lower working memory capacities (as assessed by their performance on the operation span task, in which participants are asked to remember short lists of words while carrying out mathematical operations; Turner & Engle, 1989) are more likely to notice their own name in the unattended stream in a dichotic listening experiment than

participants with higher working memory capabilities. This finding suggests that working memory plays a key role in controlling attentional allocation, such that people with lower working memory capacities find it harder to control the deployment of their attentional resources. Note that such an interpretation might also imply, in line with the proposals of Hollender (1986) and Lachter et al. (2004) mentioned earlier, that the semantic processing necessary to recognise one's own name in the unattended stream occurs as a result of the unintentional allocation of attention towards that stream (because if it simply reflected true semantic processing of all unattended information, there would have been no effect of individual working memory capacity on the likelihood of noticing the name). Note, though, that since Conway et al.'s study is correlational in nature, it cannot demonstrate a causal role for working memory in successful auditory selective attention (as it is also possible that participants' attentional abilities determined their performance on both tasks).

Nevertheless, further evidence has emerged to support the suggestion of a causal role for working memory in control of selective attention (e.g., De Fockert, Rees, Frith, & Lavie, 2001; Gazzaley & Nobre, 2012; Lavie, Hirst, De Fockert, & Viding, 2004). In light of these findings, load theory has incorporated the role of working memory by suggesting that successful selection is not only dependent on the level of perceptual load in a relevant task, but also on the availability of working memory resources.

Working memory in this respect serves to maintain the current task priorities. The prediction therefore follows that if the availability of working memory resources is reduced, distractor processing should increase because of a weaker ability to prioritise processing of relevant information over irrelevant. This prediction has typically been tested in a dual task paradigm in which participants are asked to maintain information in working memory (in order to reduce its availability) whilst concurrently

performing a selective attention task. For example, Lavie et al. (2004) asked the participants in their study to respond to the identity of a target letter (X or Z) while ignoring a concurrently-presented distractor letter which could either be congruent with respect to the target letter (e.g., an X when the target was also an X) or incongruent (e.g., a Z when the target was an X). The participants carried out this task under conditions of either high working memory load (where they were asked to remember six randomly-chosen digits) or low working memory load (where they only had to remember one digit). Incongruent distractors produced greater interference (by comparison with congruent distractors) under conditions of high working memory load than under low load conditions, suggesting that working memory availability is important for minimising interference by irrelevant stimuli (presumably through the active maintenance of current stimulus-processing priorities; see Lavie, 2005).

Similarly to the suggested involvement of perceptual load, working memory load not only influences distraction by response-competing stimuli, but also modulates the perception of unrelated stimuli (e.g. Carmel, Fairnie, & Lavie, 2012; De Fockert & Bremner, 2011; Lavie & De Fockert, 2005). For example, De Fockert and Bremner (2011) asked participants to perform an identical visual inattention blindness task to Cartwright-Finch and Lavie (2007) while keeping in mind either one (low WM load) or six digits (high WM load). In line with most of the earlier findings, a greater proportion of participants reported awareness of the critical stimulus under high WM load than under low WM load. The same finding was also demonstrated using more salient stimuli such as faces as distractors (Carmel et al., 2012). In a surprise recognition test, more participants correctly identified the face previously presented as a distractor in a dual task under high WM load compared with low WM load.

Importantly, these findings highlight that although in general it seems advantageous to

stay task focused at any given time, there are moments where the reduced availability of executive functions may be beneficial because it might increase the chance of noticing a potentially important event.

Originally, the availability of executive functions was seen to play a role at post-perceptual stages of information processing (Lavie et al., 2004). However, subsequent findings have demonstrated influences of WM load on earlier stages of processing.

Kelley and Lavie (2011) presented their participants with an object categorisation task (fruits vs. household objects), and on half of the trials a distractor object of either the same (congruent) or opposite category (incongruent) was presented in the periphery.

Activity in the visual cortex in the presence versus absence of the distractor object was assessed as a function of a concurrent WM load task. They found an increase in activity in primary visual cortex under high compared with low WM load, suggesting that the early perceptual stages of distractor processing can be modulated by the availability of executive functions. In line with these findings, there is also

behavioural evidence suggesting differences in low level visual processing as a function of WM load (De Fockert & Leiser, 2014). A low contrast gabor target was flanked by higher contrast gabor distractors. When the distractors were present (compared with absent), target detection increased and significantly so under high WM load. Thus, a lack of focused attention resulted in greater distractor processing, which in this instance aided target performance (which indeed has been demonstrated before to be the case when the flankers are collinear, e.g. Polat & Sagi, 1993).

Because improvement in detection in the presence of collinear flankers (which indeed was supported by these results) is thought to reflect processing in primary visual cortex (e.g. Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998), these results provide further support that availability of WM resources can modulate attentional priorities at

an early stage of visual processing.

Similarly to the perceptual load account of load theory, most investigations into the role of working memory availability for successful control of selective attention have focused on the visual modality. However, some findings have emerged suggesting that working memory might play the same role for both auditory and tactile stimuli. In Dalton, Santangelo, and Spence's (2009) study, participants judged the elevation of a continuous target sound (high or low) while ignoring a pulsed distractor sound, also at high or low elevation. Participants carried out the auditory task under conditions of either high working memory load (in which the participants were asked to remember six randomly-chosen digits) or low load (in which the memory set always consisted of the digits 1-6 presented in ascending numerical order). Overall, RTs were slower when the distractor sound was at the opposite elevation to that of the target (compared with when the two elevations were congruent). But importantly this interference was significantly increased when participants performed a concurrent task of high working memory load than under low load, which is in line with the results of the visual studies (e.g. Lavie et al., 2004).

In a similar experiment using the same working memory load manipulation, Dalton, Lavie, and Spence (2009) asked participants to carry out a tactile response competition task similar to that used by Soto-Faraco et al. (2004, described earlier) under conditions of either high or low working memory load. In line with the results of the auditory study, Dalton et al. found that distractor congruency effects within the tactile modality were significantly larger under high working memory load than under low load. Thus, overall, it appears that working memory is important for the control of both auditory and tactile selective attention.

7. Summary

We have considered visual, auditory and tactile research that has addressed the question of the extent to which ‘unattended’ information is processed. While certain studies have reported that participants are able to recall very little about information they had ignored (e.g., Cherry, 1953; Rees et al., 1999), other studies have found evidence suggesting that supposedly ‘ignored’ information had in fact been processed to a relatively late stage, involving semantic processing and/or response selection (e.g., Corteen & Dunn, 1974; Ruz et al., 2005). The emergence of these conflicting findings has led to a long-lasting debate in the literature over the exact stage of processing at which unattended information is excluded.

Proponents of early selection (e.g., Broadbent, 1958; Lachter et al., 2004) have argued that unattended information is filtered out early on in information processing, on the basis of simple physical characteristics. By contrast, late selection theorists (e.g., Deutsch & Deutsch, 1963) proposed that information was processed to a much deeper level before being excluded from the processing stream. More recently, many researchers have converged on a more flexible position, in which the locus of selection can vary according to the task demands (e.g. Lavie, 2010), the competition for neuronal representation of visual information (Scalf et al., 2013) and the individual characteristics of the participant (e.g. Conway et al., 2001). When deeper processing of unattended stimuli is observed, it seems likely that it results from some level of attentional allocation towards the unattended stimuli, either due to inadvertent ‘slips’ of attentional focus (e.g. Gaspelin et al., 2014; Holender, 1986; Lachter et al., 2004) or due to automatic processing of irrelevant information under conditions of low perceptual load (e.g. Lavie, 2005).

Lastly, research in recent years has identified a key role for working memory in the

control of selective attention, such that selection is more effective when working memory resources are available for the attention task than when they are not (e.g. Lavie et al., 2004).

8. References

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