Multisensory Attention and Tactile Information-Processing

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ABSTRACT

Although a great deal is now known about the peripheral sensory mechanisms involved in tactile information processing (Craig & Rollman, 1999), it is only more recently that we have started to gain a clearer understanding of the effects of selective attention on tactile perception (Johansen-Berg & Lloyd, 2000). To date, the majority of this selective attention research has considered each modality in isolation. However, in order to deal with the multimodal selection problems of everyday life, we need to be able to coordinate our selective attention cross-modally (Driver & Spence, 1998a, 2000). In this review, I will highlight the results of behavioral studies demonstrating the existence of extensive cross-modal links in selective attention between touch, vision, audition, and even olfaction. In particular, the review is structured around two key research questions: First, 'Can attention can be selectively directed to a particular sensory modality?', and second 'Are there cross-modal links in spatial attention?'. The results of recent neuroimaging studies that have started to elucidate some of the neural mechanisms underlying these cross-modal attentional effects are also discussed, and potential questions for future research outlined.

KEYWORDS: SOMATOSENSORY, TACTILE, ATTENTION, MULTISENSORY PERCEPTION, CROSSMODAL

INTRODUCTION

Although our senses are constantly bombarded by information arriving at our various sensory epithelia, we can only process a subset of the incoming information at any one time. Mechanisms of selective attention help us to focus primarily on just that information which is behaviorally relevant in terms of avoiding threat and achieving our goals. To date, the majority of attention research has focused on mechanisms of selection within individual sensory modalities, such as vision (e.g., LaBerge, 1995), audition (e.g., Scharf, 1998; Spence & Driver, 1994; Woods, Alain, Diaz, Rhodes, & Ogawa, 2001), touch (e.g., Craig & Rollman, 1999; Johansen-Berg & Lloyd, 2000; Lakatos & Shepard, 1997; Whang, Burton, & Shulman, 1991); and more recently, olfaction (Bellas, Novelly, Eskenazi, & Wasserstein, 1988) and gustation (Marks & Wheeler, 1998). By contrast, there has been relatively little research on the question of how mechanisms of attention operate across different sensory modalities to facilitate the selection of relevant information in the multimodal situations in everyday life (see Driver & Spence, 1998a, 2000; Spence & Driver, 1997a, for reviews).

Although the paradigm case illustrating the need for attentional selection, the so-called ‘cocktail party problem’ (Cherry, 1953), has often been considered simply to be an unimodal auditory selection issue (see Styles, 1997, for a review), closer inspection soon reveals it to be a multisensory selection problem (e.g., Driver & Spence, 1994). In order to understand what someone is saying at a noisy cocktail party, one needs not only to select one particular voice from amongst many others, but also to extract relevant visual information from visual lip-movements, facial expressions, and even gestures. Additionally, one may also need to ignore irrelevant competing stimuli impinging on the other senses - such as, for example, the feel of the clothes on one’s body (tactile), the smell of someone’s perfume (olfactory), and perhaps even the taste of one’s drink (gustatory). Understanding the mechanisms by which people simultaneously divide and/or focus their attention between different modalities and locations is one of the most exciting problems facing the emerging disciplines of cognitive neuroscience. Here, recent studies that have started to elucidate the mechanisms of multimodal attentional selection are reviewed, and their consequences for ‘tactile’ information processing highlighted. First, however, a distinction is made between different types of attentional selection.

Researchers studying spatial attention have made a distinction between endogenous and exogenous attentional selection (e.g., Klein & Shore, 2000; Spence & Driver, 1994). The endogenous attentional system is involved in the voluntarily direction of attention to a particular event or spatial location, such as when we choose to attend to one person at a cocktail party, or when we expect a tactile event to occur on a particular body site. By contrast, exogenous (or involuntary) attention is involved in reflexive shifts of attention to unexpected (or uninformative), yet salient events, such as someone calling your name at a cocktail party, or a fly suddenly landing on your arm. Behavioral, neurophysiological, and neuropsychological evidence now suggest that these two forms of attentional orienting may be controlled by different neural substrates (e.g., Briand, 1998; Butter, 1987; Klein & Shore, 2000; Rafal, Henik, & Smith, 1991; Spence & Driver, 1994).

Orthogonal to this distinction between endogenous and exogenous attention, is another distinction between overt and covert attentional orienting: ‘Overt’ orienting refers to shifts of receptors (as in eye, head, or hand movements), whereas ‘covert’ orienting refers to purely internal attentional shifts (e.g., Posner, 1978; Spence & Driver, 1994). While it is clear that hand movements (overt tactile orienting) can lead to the facilitation of tactile processing, it is important to note that making an eye movement to fixate a particular body site (such as the hand) can also facilitate tactile judgments for stimuli presented there, even in complete darkness (e.g., Driver & Grossenbacher, 1996). In fact, it is at present unclear whether the attentional effects reported in many of the previous studies of tactile attention reflect the consequences of covert orienting, overt orienting, or some unknown combination of the two (see Spence, Pavani, & Driver, 2000; Spence Shore, & Klein, 2001, on this point).

ATTENDING TO A SENSORY MODALITY

Can people selectively direct their covert attention to the tactile modality, and by so doing facilitate the processing of tactile stimuli presented on the skin surface? This question, which has fascinated psychologists for more than a century (e.g., Wundt, 1893), represents one of the most basic and fundamental questions in attention research. It has been claimed on the basis of numerous studies that people can selectively attend to touch, and so process tactile events more efficiently than in situations where their attention is either divided equally between several different modalities, or else directed to another sensory modality, such as vision (e.g., Klein, 1977; Posner, Nissen, & Klein, 1976). Unfortunately, however, the appropriate interpretation for the effects reported in virtually all previous modality-cuing studies is unclear, because of the possibility of alternative non-attentional explanations such as criterion shifts, response priming, and/or spatial confounds (see Spence & Driver, 1997b; Spence, Nicholls, & Driver, 2001, for reviews).

Recently, however, Spence, Nicholls, and Driver (2001) demonstrated the existence of robust modality-cuing effects in the absence of any such methodological confounds. Participants in their study made speeded spatial discrimination judgments (left vs. right using foot-pedal responses) to an unpredictable sequence of auditory, visual, and tactile targets presented to either side of fixation. In some blocks of trials, equal numbers of targets were presented in each modality and participants were instructed to divide their attention equally between all three modalities. Performance in these blocks was compared to that in other blocks where the majority of targets were presented in just one expected (i.e., to-be-attended) modality. Participants responded more rapidly to tactile targets when attention was directed to the tactile modality in advance, than when it was divided between the modalities, or else directed to another modality (e.g., vision), demonstrating the beneficial effects on tactile performance of endogenously (or voluntarily) attending to touch. Spence, Kettenmann, Kobal, and McGlone (2000) have recently extended these findings to show that similar costs are also associated with shifts of attention between touch and olfaction.

Spence, Nicholls, and Driver (2001) also demonstrated an exogenous (or stimulus-driven) attentional effect on tactile performance. In particular, they reported that participants responded more rapidly to tactile targets when they were preceded by another tactile target on the previous trial, than when they were preceded by either an auditory or visual target. This facilitatory effect, caused by the repetition of the target modality on successive trials, was attributed to the fact that the presentation of a target in one modality on one trial led to an exogenous shift of attention toward that modality, which primed/facilitated the processing of subsequent stimuli presented in the same modality. Although many previous studies have also reported similar exogenous attention-switching effects for auditory and visual stimuli (e.g., Ferstl, Hanewinkel, & Krag, 1994; Zubin, 1985), Spence, Nicholls, and Driver's study provides the first demonstration that exogenous attentional effects can also affect tactile performance, and suggests that exogenous and endogenous attention may have an additive effect on tactile perception.

Research in the spatial domain has revealed that exogenous shifts of spatial attention to a particular location are typically followed by (or co-occur with) an inhibitory tag being applied to that location, which slows responses to target stimuli subsequently presented there (e.g., Klein, 2000; Poliakoff, Spence, O'Boyle, McGlone, & Cody, submitted ; Posner & Cohen, 1984; Spence, Lloyd, McGlone, Nicholls, & Driver, 2000). It has been argued that this inhibitory tag prevents attention from perseverating on any one spatial location, and so leads to the more effective search of the environment (cf. Klein, 1988). Several researchers have also reported that IOR may occur in the non-spatial domain: For example, Law, Pratt, and Abrams (1995) found that detection latencies for targets of a particular color are inhibited by the prior presentation of a non-predictive cue in the same color, suggesting a color-based form of IOR. Similarly, Mondor, Breau, and Milliken (1998) showed that responses to target sounds at a particular frequency can be inhibited by the prior presentation of a cue at the same frequency (i.e., frequency-based IOR). Although the cause of these non-spatial forms of inhibition (and quite what selective advantage they might convey) remains controversial (see Klein, 2000; Prime & Ward, in press), recent evidence suggests that a modality-based IOR effect may also exist (Turatto, Benso, Galfano, Gamberini, & Umilta, in press). Participants in Turatto et al.'s study were presented with a non-predictive cue (either auditory or visual) shortly before an auditory or visual target requiring a speeded detection response. At short cue-target asynchronies (150 ms), participants responded more rapidly when the cue and target were in the same modality, presumably because of an exogenous shift of attention to the cued modality, similar to that reported by Spence, Nicholls, and Driver (2001). However, at longer cue-target intervals (1,000 ms), participants were slower to respond when the cue and target stimuli were presented in the same modality, than when they were presented in different modalities, suggesting the existence of a modality-based IOR effect. It is an interesting question for future research to reveal whether modality-based IOR may also affect tactile information processing.

Participants in Spence, Nicholls, and Driver's (2001) study found it more difficult (i.e., they took longer) to shift their attention away from the tactile modality, than to shift it away from either audition or vision. Spence, Shore, and Klein (2001) have also reported a similar result using an unspeeded temporal order judgment (TOJ) task. Participants in their study were presented with pairs of visual and tactile stimuli, one to either side/hand. The stimulus onset asynchrony (SOA) between these stimuli was varied using the method of constant stimuli (Shore, Spence, & Klein, 2001), and participants had to judge which stimulus appeared first. Under conditions of divided attention, visual stimuli had on average to be presented 53 ms before tactile stimuli for them to be perceived as simultaneous (presumably due to differences in sensory conduction latencies between vision and touch). However, when attention was directed to touch, vision had to lead by 155 ms for simultaneity to be achieved (a difference of 102 ms), whereas when attention was directed to vision, visual stimuli had to lead by just 22 ms (a difference of 31 ms; see Spence, Shore, & Klein, 2001). These results demonstrate both that attending to a modality can speed up the relative time of arrival of stimuli in the attended modality (the phenomenon of 'prior entry', Shore et al., 2001; Titchener, 1908), and also replicate Spence, Nicholls, and Driver's (2001) finding that people find it particularly difficult (time-consuming) to shift their attention away from touch.

Using PET, Roland (1982, e.g., p. 1068) also reported that shifting attention away from touch results in qualitatively different changes in the pattern of regional cerebral blood flow from those seen when attention is shifted away from audition or vision. Directing attention away from audition or vision (to focus on another modality) led to a reduction in the activity in unimodal auditory and visual cortical areas respectively, whereas focusing attention away from the tactile modality did not (see Eimer & Driver, 2000, for electrophysiological data supporting the unique nature of cross-modal links in tactile attention). It is an interesting question for future research to determine whether this difference between touch and the other modalities may be related to the fact that while touch is a proximal sense (informing us primarily about events on our skin surface), audition and vision more often provide information about distal events (Gibson, 1966; see also Martin, 1995).

In the years since Roland's (1982) seminal study, there has been a dramatic increase in the number of studies investigating the neural consequences of selectively directing attention to a particular modality (see Johansen-Berg & Lloyd, 2000, for a recent review; see also Downar, Crawley, Mikulis, & Davis, 2000). For example, Johansen-Berg, Christensen, Woolrich, and Matthews (2000) used fMRI to investigate changes in neural activity in somatosensory cortex associated with selectively attending to touch. Participants in their study were presented with random sequences of visual and tactile stimuli, and their attention was directed to one or other modality on a trial-by-trial basis. When the participants' attention was directed to touch, Johansen-Berg et al. found a unilateral enhancement of activation in primary (S1) together with bilateral enhancement in secondary (S2) somatosensory cortex (see also Mima, Nagamine, Nakamura, & Shibasaki, 1998). Similar results have also been reported in the monkey on the basis of single-cell studies (e.g., Burton, Sinclair, Hong, Pruett, & Whang, 1997; Hsiao, O'Shaughnessy, & Johnson, 1993). Meanwhile, other researchers have shown that selectively directing attention to either audition or vision also leads to the modulation of activity in primary auditory and visual cortex respectively (e.g., Jancke, Mirzazade, & Shah, 1999). However, it is important to note that the selective direction of attention to a particular sensory modality results not only in the enhancement of neural activity within the relevant modality-specific cortex, but also in a decrease of activity related to the processing of stimuli in other 'unattended' modalities (e.g., Kawashima, O'Sullivan, & Roland, 1995).

While many of these neuroimaging and neurophysiological studies provide preliminary evidence regarding the neural consequences of selectively attending to touch, it is important to note that their results might actually reflect the effects of endogenously shifting spatial attention to a particular location instead, given that tactile stimuli were presented from a different spatial location from visual stimuli (i.e., tactile stimuli were presented to the big toe while visual stimuli were presented on a screen; see Spence & Driver, 1997b). In future research, it will clearly be important to present stimuli from different modalities from the same possible locations to eliminate this potential spatial confound and so isolate the specific neural effects associated with attending to a sensory modality (Driver & Spence, 1998b).

Aside from the non-spatial studies looking at the costs associated with shifting attention from one sensory modality to another, there has also been a great deal of interest recently in identifying temporal processing limitations on our ability to attend to multiple target stimuli in rapidly-presented streams of stimuli. In a typical study, participants try to identify two targets presented sequentially in a rapidly-changing stream of visual distractors (presented at a rate of approximately 8-10 items per second). Numerous visual studies have shown that while people have no problem in responding to the first target, they frequently miss the second target when it is presented within about 500 ms of the first. Although this temporal processing deficit, known at the 'attentional blink' (see Shapiro, Arnell, & Raymond, 1997, for a review), has primarily been investigated within the visual modality (i.e., looking for visual targets amongst visual distractors), recent studies have shown similar effects within audition (Duncan, Martens, & Ward, 1997; Soto-Faraco & Spence, 2002) and touch (Hillstrom, Shapiro, & Spence, in press; Shapiro, Hillstrom & Spence, 1998; see also Craig, 2000).

Of particular interest in the present context is Soto-Faraco, Spence, Fairbank, Hillstrom, and Shapiro's (in press) demonstration of a cross-modal attentional blink between vision and touch. Participants in their study were presented with two masked targets at variable interstimulus intervals, using the paradigm popularized by Duncan, Ward, and Shapiro (1994). One target was presented in each modality on each trial, and the order of presentation of target modalities was randomized. Participants had to make spatial discrimination responses regarding the location of the targets. Soto-Faraco et al. found that the detection of a masked target in either modality led to a short-lasting cross-modal attentional blink that reduced their participant's ability to respond to targets presented subsequently in the other modality (when compared to trials on which the participant had only to respond to the second target). These results suggest that the temporal constraints on our ability to process sequentially presented stimuli within a particular sensory modality may also limit our ability to process stimuli presented sequentially to different sensory modalities, at least for the case of touch and vision (see Dell'Acqua, Turatto, & Jolicouer, in press, for related findings between audition and touch, and Duncan et al., 1997; Soto-Faraco & Spence, 2002, for differing results within the audiovisual domain).

CROSS-MODAL LINKS IN SPATIAL ATTENTION

While there is a long history of studies investigating the non-spatial aspects of multimodal selection, there has been a recent growth of interest in studies examining the effects of cross-modal links in spatial attention on human information processing. In particular, these have addressed the question of what effect a shift of attention (either exogenous or endogenous) in one modality to a particular spatial location has on the spatial distribution of attention in other modalities (see Driver & Spence, 1998a, for a review). For example, it has recently been shown that the peripheral presentation of a spatially-nonpredictive tactile cue (to one or other hand) leads to a short-lasting exogenous shift of spatial attention which facilitates responses to auditory, visual, and tactile targets presented at (or near) the cued hand, when compared to performance near the uncued hand (e.g., Butter, Buchtel, & Santucci, 1989; Kennett, Spence, & Driver, in press; Spence & McGlone, 2001; Spence, Nicholls, Gillespie, & Driver, 1998). Similar cross-modal links in exogenous spatial attention have also been reported following the presentation of spatially non-predictive auditory or visual cues (Spence, 2001; Spence et al., 1998). Although cross-modal links in exogenous spatial attention have primarily been studied using speeded responding paradigms, several recent psychophysical studies have also shown that cross-modal shifts of exogenous spatial attention lead both to a ‘speed-up’ in the relative time of arrival of cued stimuli (i.e., to spatial ‘prior entry’ effects), and also to the increased perceptual saliency of cued stimuli (e.g., McDonald, Teder-Sälejärvi, & Hillyard, 2000; Spence & Lupiánez, 1997).

As highlighted earlier, exogenous shifts of attention are typically followed by a long-lasting inhibitory effect at the cued location (e.g., Klein, 2000; Posner & Cohen, 1984). Several researchers have now demonstrated cross-modal spatial links in IOR as well (Spence et al., 2000; Tassinari & Campara, 1996). Spence et al. reported that the peripheral presentation of auditory, visual, or tactile stimuli to one or other side led to an inhibition of detection responses for all target stimuli presented on the same side 950-2,250 ms later. Importantly, cross-modal IOR effects (i.e., between successive targets in different modalities) were no smaller than those reported intramodally (i.e., between successive targets presented in the same modality). The existence of such robust cross-modal links in IOR may reflect the fact that the superior colliculus, one of the key neural structures implicated in spatial IOR (e.g., Röder, Spence, & Rösler, 2000; Sapir, Soroker, Berger, & Henik, 1999), is a major site of multisensory convergence involved in controlling orienting responses (e.g., Stein & Meredith, 1993).

It should be noted though that while cross-modal interactions in human information-processing clearly reflect the consequences of interactions taking place in multimodal convergence sites, such as the superior colliculus, parietal lobe, and insula/claustrum region, this may not be the whole story. In particular, the results of several recent neuroimaging studies show that cross-modal links in exogenous spatial attention may also reflect the consequences of feedback from these multimodal sites to modulate activity in ‘earlier’ cortical areas, traditionally thought to be purely ‘unimodal’ (e.g., Driver & Spence, 2000). For example, Macaluso, Frith, and Driver (2000a) have shown that neural responses to visual stimuli within ‘unimodal’ visual cortex in the lingual gyrus, can be enhanced by the simultaneous presentation of a tactile cue from the same spatial location. Similarly, by measuring event-related brain potentials (ERPs) at the scalp, Kennett, Eimer, Spence, and Driver (2001) have shown that the amplitude of the early visually-evoked occipital N1 to a visual target (peaking at approximately 190 ms after stimulus onset) can be modulated by the presentation of a spatially-nonpredictive tactile cue from the same spatial location (see McDonald & Ward, 2000; McDonald, Teder-Sälejärvi, Heraldez, & Hillyard, 2001, for similar results from audiovisual exogenous cuing studies).

Researchers have also demonstrated the existence of extensive cross-modal links in endogenous spatial attention between audition, vision, and touch (e.g., Lloyd, Merat, McGlone, & Spence, submitted; Spence & Driver, 1996; Spence, Pavani, & Driver, 2000; Spence, Shore, & Klein, 2001). For example, participants in a study by Spence, Pavani, and Driver made speeded discrimination responses (either continuous vs. pulsed, or up vs. down) to a series of visual and tactile targets presented from either side of fixation. When participants were informed that visual and tactile targets were more likely on one side than the other, discrimination responses were faster (and more accurate) on the expected/attended side, even though the target modality was entirely unpredictable. This result, together with similar results from an unspeeded TOJ study reported by Spence, Shore, and Klein (2001) demonstrate that people can simultaneously direct their visual and tactile attention to a particular spatial location, contrary to some previous claims (e.g., Posner, Nissen, & Ogden, 1978). Importantly, when participants expected a target on a particular side in just one modality, corresponding shifts of covert attention also took place in the other (secondary) modality, supporting the existence of cross-modal links between endogenous visual and tactile spatial attention. Finally, Spence et al. also demonstrated that participants found it more difficult to direct their visual and tactile attention to different spatial locations than to the same location. These behavioral results clearly demonstrate the existence of extensive cross-modal links in endogenous spatial attention between vision and touch, similar to those reported previously for the exogenous case.

These behavioral results have been supported recently by electrophysiological data reported by Eimer and Driver (2000). Participants in their study were presented with a random sequence of tactile and visual stimuli to both hands. During each block of trials, participants made speeded vocal detection responses to targets presented in a particular modality on a particular side. That is, participants had to attend to a particular modality on a particular side while simultaneously trying to ignore irrelevant distractors in the other modality on the attended side, and also to ignore all stimuli presented on the 'unattended' side. Eimer and Driver found an attentional modulation of the occipital P1 and N1 to visual stimuli (interpreted as evidence of perceptual sensory gating processes within visual perception) on the attended side, both when attention was directed to vision, and more importantly, when attention was directed to touch as well. Similarly, somatosensory event-related potentials were also modulated both by tactile spatial attention and to a lesser extent by visual spatial attention (at least when touch was potentially relevant to the participant's task). Using PET, Macaluso, Frith, and Driver (2000b) have identified several brain areas that are specifically implicated in either just sustained endogenous visual spatial attention (superior occipital gyrus), or just tactile attention (superior postcentral gyrus), as well as other sites that show enhanced activation when sustained attention is focused on a particular location in either modality (intraparietal sulcus and occipitotemporal junction), consistent with the behavioral evidence for cross-links in visuotactile spatial attention reported by Spence, Pavani, and Driver (2000).

Taken together, the results from all these studies converge on the conclusion that there are extensive cross-modal links in attention (both exogenous and endogenous) between touch, audition, and vision. Given that cross-modal links have been demonstrated for both exogenous and endogenous attention when studied in isolation, an important question for future research will be to examine how these two forms of spatial attention interact to control multisensory selection in more realistic settings (Butter et al., 1989; Klein & Shore, 2000). A second important, but as yet unresolved, issue is why tactile attention should have a greater effect on human performance in tasks involving some form of spatial discrimination response, than in other non-spatial tasks (e.g., Hillstrom et al., in press; Posner, 1978; Spence et al., 2000).

To date, the majority of studies concerning cross-modal links in spatial attention have been conducted with participants adopting an uncrossed posture (i.e., with the left hand lying in the left visual field and the right hand in a homologous location in the right visual field; e.g., Butter et al., 1989; Posner et al., 1978; Spence et al., 1998). However, researchers have recently started to investigate what effect posture change (such as crossing the hands, so that the left hand lies in the right visual field and vice versa for the right hand, or interleaving the fingers of the two hands) may have on cross-modal links in spatial attention. Importantly, several studies have now shown that cross-modal links in visuotactile spatial attention appear to operate upon a representation of visuotactile space that is updated when posture changes (e.g., di Pellegrino, Làdavas, & Farne´, 1997; Kennett et al., 2001; Kennett et al., in press; Röder, Spence, & Rösler, 2002; Spence, Kingstone, Shore, & Gazzaniga, 2001; Spence, Pavani, & Driver, 2000); For example, Kennett and colleagues have shown that a tactile cue on the left hand will lead to a shift of visual attention to the left when the hands are uncrossed, but to a shift of visual attention to the right when the hands are crossed (see Pavani, Spence, & Driver, submitted; Spence, Pavani, & Driver, 1998, for similar results using a cross-modal congruency task). More surprisingly, these cross-modal links in spatial attention have also been shown to be updated to take account of apparent changes of posture that can be induced using a rubber arm (while hiding the participant's real arm out of sight; e.g., Farnè, Pavani, Meneghello, & Làdavas, 2000; Pavani, Spence, & Driver, 2000; see also Botvinick & Cohen, 1998; Graziano, 1999; Maravita, Spence, Clarke, Husain, & Driver, 2000). Finally, Spence, Kingstone et al. (2001; see also Spence, Shore, Gazzaniga, Soto, & Kingstone, 2001) have shown that intact cross-cortical connections may be a necessary prerequisite for maintaining an up-to-date representation of visuotactile space, at least when the hands cross the midline.

CONCLUSIONS

We now know a great deal about the peripheral sensory mechanisms involved in the spatiotemporal processing of tactile stimuli (e.g., see Craig & Rollman, 1999, for a review). However, it is only more recently that we have started to gain a clearer understanding of the effects of selective attention (both unimodal and multimodal) on tactile perception. The results of numerous studies now show that people can selectively direct their attention to a particular sensory modality such as touch, and so facilitate the processing of stimuli presented in that modality. Moreover, research has also shown that attention can also be directed (either endogenously or exogenously) to a particular spatial location or body site. Behavioural, electrophysiological and neuroimaging data now converge on the view that a shift of attention (no matter whether it is elicited exogenously or endogenously) in one sensory modality to a particular location typically results in a concomitant shift of attention in the other modalities to the same spatial location (at least for the case of audition, vision, and touch). This rapidly-growing body of research suggesting that tactile, auditory, and visual attention are normally directed to the same spatial location at the same time, raises an important question: Namely, do these cross-modal spatial attentional effects reflect the consequences of separable tactile, auditory, and visual attentional systems operating in a co-ordinated manner (as suggested by Spence & Driver's, 1996, 'separable-but-linked' hypothesis), or do they instead reflect the operation of a single supramodal attentional system which acts to selectively enhance the processing of all sensory stimuli emanating from a particular spatial location (see McDonald et al., 2001; Spence, 2001). A key role for future research will be to design the critical experiments to distinguish between these competing hypotheses, given that they make such similar behavioral predictions (see Spence & Driver, 1996; Spence, 2001, on this point). If future research should reveal that some version of the supramodal attentional spotlight (perhaps one combining the supramodal spotlight with a non-spatial mechanism for selectively attending to one or more sensory modalities) should provide the most parsimonious account of the empirical data, then we may have to consider more carefully what meaning to attach to terms such as 'tactile spatial attention' in the coming years. Nevertheless, whatever the answer to this last question is, it is clear that we are now well on the way to understanding how mechanisms of attention enable us to solve the multisensory selection problems of everyday life.

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