

Crossmodal attention

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Most selective attention research has considered only a single sensory modality at a time, but in the real world, our attention must be coordinated crossmodally. Recent studies reveal extensive crossmodal links in attention across the various modalities (i.e. audition, vision, touch and proprioception). Attention typically shifts to a common location across the modalities, despite the vast differences in their initial coding of space. These spatial synergies in attention can be maintained even when receptors are realigned across the modalities by changes in posture. Some crossmodal integration can arise preattentively. The mechanisms underlying these crossmodal links can be examined in a convergent manner by integrating behavioural studies of normal subjects and brain-damaged patients with neuroimaging and neurophysiological studies.

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Abbreviations

ERP	event-related potential
fMRI	functional magnetic resonance imaging
IOR	inhibition-of-return
PET	positron emission tomography

Introduction

Most research on selective attention has implicitly assumed that each sensory modality can be considered in strict isolation, and has thus overlooked many issues concerning crossmodal links. In daily life, people often have to coordinate their attention across the modalities, selecting information from a common source (e.g. the speech-sounds together with the lip-movements of someone speaking in a noisy room), despite the vast differences in the initial coding of that source between different modalities. Here, we review recent studies that demonstrate extensive crossmodal links in attention. Results from behavioural studies with normal and clinical populations are related to emerging data from neuroimaging and neurophysiology. These studies highlight how information from various sensory systems (e.g. visual, auditory, somatosensory, proprioceptive and vestibular) is integrated to construct

multimodal representations of space, within which attention can be directed.

Attending to one sensory modality versus another

The most basic crossmodal issue concerning attention is whether people can attend selectively to one modality at the expense of others, or whether the modalities are so independent that concentrating on one has no implications for the others. As long ago as 1893, Wundt [1] claimed that attention can speed up the processing of a relevant modality, while delaying irrelevant modalities; many subsequent authors have concurred. However, as we have pointed out elsewhere [2•], most studies on this issue have suffered from methodological flaws. For instance, stimuli in different modalities were typically presented from different spatial positions, so attention to a modality was confounded with attention to a location. Moreover, preparation for different tasks, criterion shifts, and the repetition of particular stimuli or responses were also confounding factors in most studies. Recent experiments, however, show that substantial behavioural effects of attending to one modality (e.g. vision, hearing, or touch) versus another can still be found when these confounds are removed [2•,3]. Bonnel and Hafter [4•] propose that such effects of attending to a modality primarily influence sensory discriminations (e.g. judging the nature of a change) rather than sensory detection (i.e. judging the presence of a change), even when overall differences in task difficulty for discrimination versus detection are taken into account.

Several event-related potential (ERP) studies (see [5•,6]), measuring neural activity via electrodes at the scalp, have reported that attention to a modality is associated with enhanced activity over corresponding regions of cortex (e.g. over occipital cortex when attending to vision). The evidence on this issue from functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies is currently somewhat mixed, with some studies showing a clear modulation of activity in modality-specific cortical areas as a function of the modality attended [7], whereas others do not (see [8•]). Clearly, this area merits further study. It has been suggested that the effects of attending to a modality might be mediated by thalamic gating [9]. If the thalamus specifically affected the synchrony of firing in modality-specific cortical areas, as has been suggested, then some effects found with ERPs might be absent in fMRI and PET, because ERPs are more sensitive to the fine temporal pattern of neural activity [10•]. It should be noted that, unfortunately, all of

the functional imaging studies on attending to a modality have, to date, suffered from the flaws in the psychological methodology elucidated by Spence and Driver [2**].

The mechanisms by which we can attend to one modality versus another have recently attracted considerable clinical interest. There have been several recent claims that various clinical populations, including schizophrenics [11•], patients with frontal lobe damage [12], Huntington's disease patients [13], and autistics [14], show selective deficits in their ability to shift attention from one modality to another, or to divide their attention between different senses. Unfortunately, these clinical findings, at present, all remain open to the many methodological criticisms raised by Spence and Driver [2**]. In future work, it would be useful to apply the improved behavioural methods discussed by Spence and Driver [2**] to the various patient groups, and to incorporate these methods in functional imaging studies.

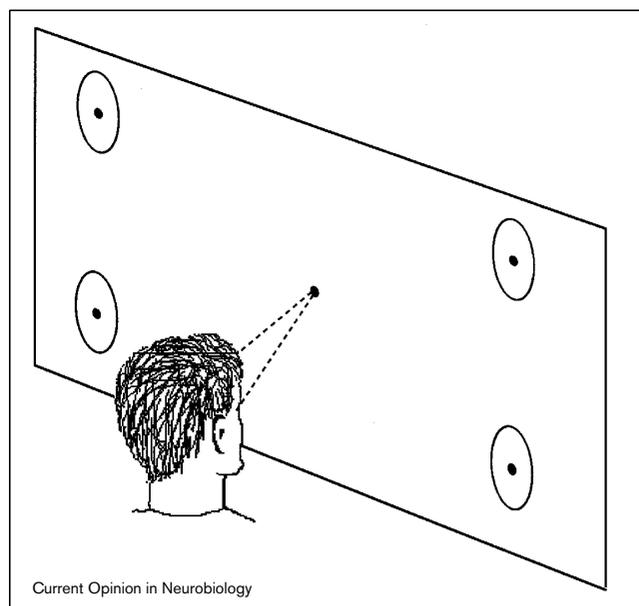
Links in spatial attention across the modalities

We turn now to consider spatial aspects of attention. It is conventional to distinguish between overt shifts of attention (i.e. where receptors move toward regions of interest, as in eye-, head- or hand-movements) versus covert shifts (i.e. internal changes in attention with no receptor shift [15]). Our review concentrates on covert mechanisms. A further distinction is between endogenous or voluntary mechanisms of attention (driven by expectations) versus exogenous or reflexive mechanisms (driven by salient peripheral stimuli). Several qualitative differences between exogenous and endogenous mechanisms of attention have now been observed in unimodal studies, and different neural substrates may be involved [15,16**,17•]. Hence, these two forms of attention should initially be considered separately when assessing any crossmodal spatial links.

Crossmodal links in endogenous spatial attention

We [16**,17•] have developed the orthogonal-cuing paradigm as a method for measuring the spatial distribution of covert attention in vision, hearing and touch. Participants make speeded discriminations concerning the elevation (up versus down) for each of a series of targets, presented in a random order such that target modality and target side are unpredictable (see Figure 1). Covert attention is directed toward one side, for instance by informing participants that targets are most likely there (note that the lateral direction of attention is orthogonal to the required up/down decision, and thus should not induce any response bias, unlike some other methods [18,19]). Elevation judgements are typically faster and/or more accurate on the expected side, even though no receptor shifts are allowed, and even when target modality is uncertain. This suggests that stimulus localisation improves within endogenously attended regions, as if neurons for the attended area adopted narrower receptive fields or higher gains.

Figure 1



Schematic view of the position of possible target loudspeakers (shown by ellipses) and target lights (shown as black dots), plus a central fixation light in Spence and Driver's [16**,17•] studies of audiovisual links in covert spatial attention. The participant's head is cartooned, and the direction of steady fixation is indicated with dashed lines. A single target, either auditory or visual, was presented on each trial, and the participant made a speeded response discriminating whether each target came from the upper or lower row, regardless of its side, and regardless of which side attention had been directed toward. (Attention was directed by a spatial expectancy concerning the likely target side in the endogenous experiments, and by a peripheral event on one side, at an intermediate elevation, in the exogenous studies.)

Importantly, when a target is strongly expected on a particular side in just one modality (e.g. audition), up/down discriminations also improve on that side in other modalities (e.g. vision), suggesting a tendency for common shifts in endogenous spatial attention across the modalities [16**]. However, the spatial effect for secondary modalities is smaller than in the primary modality for which the spatial expectancy applies. This implies that the spatial distribution of attention in the primary modality spreads across to other modalities in an attenuated manner, rather than one strictly supramodal system being directed to the expected side equivalently for all modalities. These behavioural findings converge with data from audiovisual ERP studies. It is well known that modality-specific waveforms can show larger amplitude ERPs for stimuli from an endogenously attended location (see [20•] for related findings from a recent PET study). The critical crossmodal result [5**,21] is that similar amplitude modulation as a function of attended position is also found for stimuli in a task-irrelevant second modality, but at a reduced level.

Further studies with our orthogonal-cuing method [16**] have found that endogenous covert attention can be split spatially (i.e. directed in opposite directions) for

audition and vision under certain conditions, but this is less efficient than directing attention to a common location crossmodally (see [22] for similar results from continuous dual-task studies). Taken together, these results all suggest substantial crossmodal constraints on the allocation of endogenous attention.

This conclusion might initially seem to be at odds with a recent report claiming entirely separate attentional resources for hearing and vision [23••]. However, this report concerned a very different situation which did not manipulate spatial factors. Participants had to monitor two rapid streams, one auditory and the other visual, for prespecified targets among distractors. Within vision, identifying one target in a rapid stream typically impairs performance for subsequent targets within the next 100–500 ms (the attentional blink), and this time-locked effect was also found with audition. No such effect was apparent when the successive targets were presented in different modalities, apparently demonstrating the independence of auditory and visual attention. However, performance was worse overall when both modalities had to be monitored rather than just one, so some crossmodal limitation did in fact restrict performance. The difference between the unimodal and crossmodal limitations was that performance for the second target was no longer closely time-locked to presentation of the first target in the crossmodal case. It remains unknown whether this change merely reflects the greater dissimilarity between successive targets in the crossmodal situation. It would be useful to repeat this study while varying the spatial separation of stimuli in the two modalities to test for the crossmodal links in spatial aspects of endogenous attention that were revealed by the other studies that we have described.

Crossmodal links in exogenous spatial attention

Extensive crossmodal links have now also been reported for shifts of exogenous spatial attention, triggered by task-irrelevant but salient peripheral stimuli, rather than by spatial expectancies. When testing this issue, it is important that the triggering stimulus (or cue) does not predict the likely location of subsequent targets, unlike several previous studies [24,25]. Recent work shows that an entirely nonpredictive cue in one modality can attract exogenous covert attention to its location in other modalities [17•,26•,27•], improving performance in speeded up/down discriminations for targets on the side of the cue. Crossmodal links in exogenous spatial attention have now been demonstrated in this way between all possible pairings of auditory, visual, and tactile cues and targets (e.g. see Figures 1 and 2a), with the sole exception that nonpredictive visual cues have no effect on the distribution of auditory attention (at least when eye movements are prevented [17•]).

Recent studies with brain-damaged patients, suffering from apparent deficits in spatial attention, lend further

Figure 2

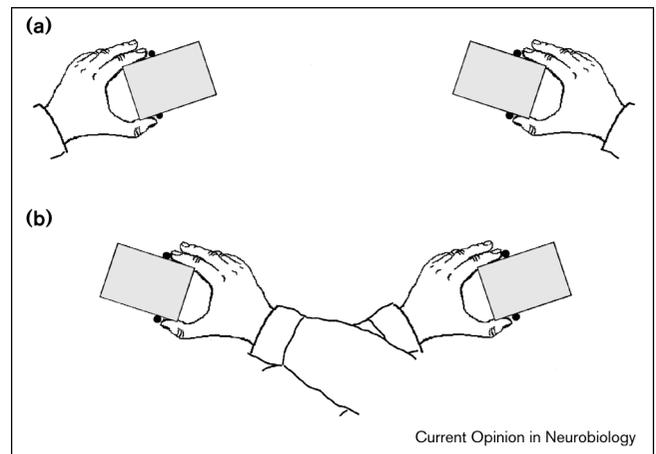


Illustration of apparatus for visual–tactile and tactile–visual cuing experiments. The hands were either (a) uncrossed or (b) crossed (see text for details). The participant gripped a sponge cube in each hand with thumb and index finger. Both cubes incorporated one vibrotactile device at the thumb (next to a small light, illustrated by a black dot), and a separate vibrator at the index finger (next to another small light). In one series of experiments, visual stimulation (from both the lights near one or the other hand) served as a spatially nonpredictive cue that was task-irrelevant. Each such cue was followed by a target vibration from any one of the four possible vibrators, and subjects made a speeded discrimination of whether this tactile event came from an upper (index finger) or lower (thumb) position, regardless of which hand was stimulated. In another series of experiments, the roles of cue and target were reversed; a target light was presented from one of four possible positions for a speeded up/down discrimination, following tactile stimulation of one or the other hand.

support to our conclusion of exogenous attentional links between the modalities. Patients with right-hemisphere lesions, particularly to parietal cortex, often exhibit a deficit known as extinction. Single stimuli presented to either side are detected with little difficulty, but when stimuli are presented to both sides simultaneously, the patient now misses the stimulus that is further to their contralesional left side (this left stimulus is said to be extinguished by the ipsilesional right stimulus). Extinction is thought to reflect a pathological bias in the competition between stimuli to attract attention, which favours ipsilesional (right) events because of the brain injury [28,29].

Some previous studies [30] had suggested that while extinction can be found within each sensory modality, it is never found between events in separate modalities. Moreover, extinction has often been reported to affect selectively the processing of stimuli within just one sensory modality in individual patients [31–33]. However, more recent evidence suggests that crossmodal extinction can arise in many neurological patients with attentional deficits [34•,35••]. Some of the apparent discrepancies may be related to the particular modalities under examination, with crossmodal links in extinction having been observed

between vision and touch [34•,35••], but not yet consistently between vision and hearing [31]. However, it should also be noted that some of the failures to find crossmodal extinction may be attributable to the informal clinical measures used to assess the deficit, as these can suffer from floor or ceiling effects. Further investigation of crossmodal extinction is required.

Crossmodal links in spatial inhibition-of-return

Posner and Cohen [36] first observed that if the interval between a spatially nonpredictive visual cue and a subsequent visual target increases beyond 300 ms, people begin to detect targets on the cued side more slowly than on the uncued side (thus reversing the facilitatory effect found at shorter cue–target intervals). This effect has come to be known as inhibition-of-return (IOR), reflecting the original hypothesis that covert attention may first be drawn to the cued location, and then tend to move on with a bias against returning. The effect has now been found within audition [37•], as well as within touch [38•]. IOR can also be found between an event in one modality and a subsequent target in another modality [37•,38•,39,40], suggesting a crossmodal phenomenon. The one apparent exception is a recent report [41] that auditory cues do not elicit IOR for visual targets unless a saccade is made toward the auditory cue, suggesting that eye movements might be responsible for crossmodal IOR. However, a further study [40] shows that the critical factor here is not eye movement execution but the relatively long-lasting facilitatory crossmodal effect that can persist at the location of a sound, as a result of its drawing exogenous attention there. This facilitation can oppose and thus obscure the emergence of IOR at the same location. The crossmodal IOR can be revealed simply by presenting a central sound subsequent to the peripheral auditory cue, to reorient facilitatory attention and thus remove its opposing influence [40]. In addition to its implications for crossmodal links, this finding implies that IOR reflects an entirely separate phenomenon from facilitatory attention, albeit one that can overlap in time.

Spatial coordinates of crossmodal attention: crossmodal links when receptors are realigned

The studies of crossmodal attention discussed above invariably concerned situations in which the receptor systems for the various modalities were aligned in one particular default posture. The participant's head and eyes were fixed straight ahead, with each hand resting on a table in its usual hemisphere (i.e. left hand on the left, right hand on the right). However, in daily life we can adopt many different postures, and the important point is that these spatially realign the receptors for the different modalities. For instance, every time you move your eyes, retinotopic visual inputs are realigned relative to somatotopic tactile space, and to head-centred auditory space. Likewise, each movement of your hand can realign its tactile coordinates relative to vision and audition.

This raises the computational problem of how the nervous system represents the common position of a particular external source across the different senses. This seems challenging given that the spatial organisation of the senses is so different at input levels (audition is initially tonotopic and then craniotopic, vision is retinotopic, and touch somatotopic). A further challenge is that the mapping of which particular receptors in one modality correspond spatially with those in another modality changes every time a new posture is adopted, with the eyes, head and body moving independently. The means by which the brain derives useful representations of stimulus location across the senses, despite such complexities, has been intensively investigated at the single-cell level by recent physiological studies (see e.g. [42,43••–45••] and Graziano and Gross, in this issue, pp 195–201). However, such issues have rarely been raised in behavioural studies of selective attention until now.

Recent studies have begun to investigate the spatial coordinates in which crossmodal exogenous attention operates when different postures are adopted. Recall that, in the study illustrated in Figure 2a, a sudden visual event in the left visual field led to better tactile up/down discriminations with the left rather than right hand. Is this crossmodal effect based on some fixed anatomical mapping between left visual field and left hand (e.g. because both project to the same right hemisphere), or does it arise because tactile attention is drawn toward the external location of the visual event, as represented in the brain? This was addressed by repeating the experiment, but now with the hands in a crossed posture (see Figure 2b). The results were completely reversed in terms of which area of the retina and body surface had to be stimulated in order to produce better tactile performance; although they remained unchanged when considered in terms of external space. That is, a visual flash on the left still led to faster tactile discriminations on that side of space (but now with the right hand), whereas a flash on the right now led to faster tactile discriminations with the left hand, in the right hemisphere [27•]. Evidently, the mapping between vision and touch that drove the reflexive crossmodal shift of covert spatial attention was updated when the hands adopted different postures. This presumably depends on proprioceptive inputs signalling the current location of the hands, and thus provides an example of the attentional interplay between two modalities (vision and touch) being influenced, in turn, by a third modality (proprioception).

A similar remapping has also been reported when uncrossed versus crossed hands are compared for the reverse situation of a nonpredictive tactile cue preceding a visual target for up/down discrimination ([27•]; see also [46•]). It is tempting to relate such findings to the recent discovery of cells in various regions of the monkey brain (e.g. the putamen and premotor cortex) that code tactile and visual stimuli in approximate spatial register, and have visual receptive fields that follow particular

body parts around as they move, even when the body is unseen (see [43••,44••] and Graziano and Gross, in this issue, pp 195–201). Although no specifically attentional effects have as yet been demonstrated for such cells, their selective activation could explain the crossmodal cuing effects we observe, and the abstract spatial coordinates in which these evidently operate.

A recent single-case study of a right-frontal patient with crossmodal extinction provides a further illustration of this point [35••]. The patient could detect tactile stimulation of his affected left hand in isolation, but this was extinguished by concurrent visual stimulation on the right. Further testing revealed that such crossmodal extinction only arose if the visual stimulation was close to the position of the (unstimulated) right hand. di Pellegrino *et al.* [35••] argue that visual stimulation near the right hand boosts its representation among crossmodal cells such as those discussed above, which would, in turn, impair the representation of the left hand in the competitive manner envisaged by Driver *et al.* [28] and Duncan *et al.* [29].

A recent study of normal performance shows that links in exogenous attention between vision and audition are similarly maintained spatially across different postures, such as when the eye deviates to one side in the head (which realigns retinotopic visual coordinates against head-centred auditory coordinates). Thus, an abrupt auditory event at a particular location does not attract visual attention merely by activating a fixed retinal location. Instead, the sound activates a representation of whichever retinal region currently corresponds to the external location of the sound; in turn, this depends on how the eye is currently deviated in the head, as signalled proprioceptively [27•]. This finding may relate to recent physiological findings from cells in the lateral intraparietal area of the monkey parietal lobe, whose auditory responsiveness is modulated by the current deviation of the eye in the head [47,48•].

Can crossmodal integration arise preattentively?

The experiments described so far suggest that crossmodal integration of information from different senses may contribute to the representational space in which attention is directed, as when proprioception modulates a tactile input so that visual attention is drawn appropriately toward the current location of a stimulated hand [27•,46•]. However, all these examples have concerned the effects of a salient cue that attracted attention. The findings therefore cannot speak to the important issue of whether crossmodal integration can arise preattentively (i.e. before a particular external source has been selected by attention). Driver [49•] addressed this issue by presenting a target verbal message, which had to be repeated, concurrently with a distractor verbal message from the same sound source. Which message was relevant was specified only visually, by lip movements corresponding to the target speech sounds. These moving lips were

presented either from the same or opposite side as the mono sound-source (see Figure 3). Better selective shadowing of the relevant message was observed when the relevant lips were displaced from the relevant and irrelevant sounds.

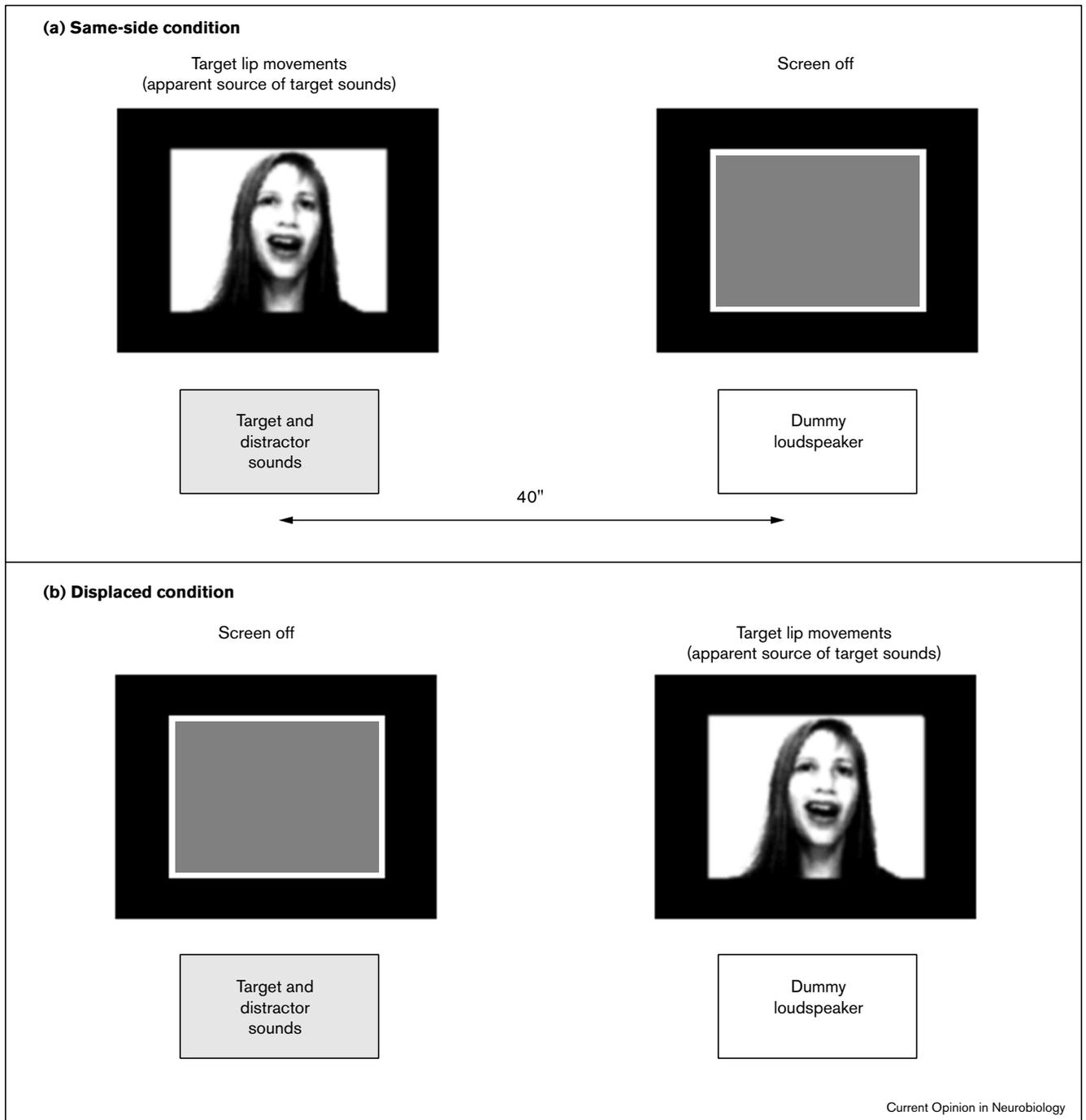
Driver [49•] attributes this result to the well-known ventriloquism illusion [50••], whereby people mislocate sounds toward their apparent visual source (as in the case of a ventriloquist's dummy, or at a movie-theatre). The target sounds would be pulled away from the distractor sounds by any ventriloquism in the displaced condition (Figure 3b), thus leading to an illusory spatial separation between target and distractor sounds, which evidently helps selective listening. These results imply that some crossmodal integration can take place between hearing and vision before auditory spatial selection is fully completed. The benefit for the displaced condition (Figure 3b) could only arise if just the target sounds were illusorily pulled toward the matching moving lips, leaving the distractor sounds behind. This could only happen after the system had already worked out to some extent which sounds matched the synchronous lip movements (and so should migrate toward them), and which sounds did not match (and so should be left behind). The illusory separation by ventriloquism evidently facilitated attentional selection, so some of this crossmodal matching must have taken place before attentional selection was complete. Thus, the crossmodal binding problem [51] can apparently sometimes be solved in a preattentive manner, in such a way as to facilitate attentional selection via the crossmodal construction of space.

Similar implications follow from another study in which subjects were required to judge the vibrotactile stimuli presented to one hand, while ignoring concurrent vibrotactile distractors on the other hand [52•]. Distractor vibrations interfered less when the hands were placed far apart in external space than when they were placed close together, even though this did not change the task-relevant vibrations on the skin. The same result was found for subjects with and without blindfolds, thus implying a role for proprioceptive inputs signalling the current hand separation. Evidently, some degree of crossmodal integration between touch and proprioception took place before tactile attentional selection of just the relevant vibration was completed. A further study (see [28]) shows that tactile extinction in patients with right parietal injury can similarly be modulated by unseen hand separation, again implying that tactile inputs are first integrated with proprioceptive signals about the current position of the stimulated tactile receptors in external space, before the process of directing attention has been fully completed for the tactile events.

Neural basis of crossmodal integration for spatial attention

Future studies of brain-damaged patients may help to identify the specific brain structures associated with the

Figure 3



Schematic illustration of the apparatus used by Driver [49]. **(a)** The top row shows the same-side condition, and **(b)** the bottom row shows the displaced condition. Relevant and irrelevant words were played from a single loudspeaker (shown on the left in the illustration, but equally likely to be on the right), spoken in the same voice. A video monitor on one side – left in (a), right in (b) – showed lip movements that matched the relevant auditory words that had to be repeated by the subject. Performance was better when the relevant lip-movements were displaced away from the true mono sound source – as in (b) but not (a) – because this produced an illusory separation between relevant and irrelevant sounds.

particular forms of crossmodal integration that affect spatial attention. At present, the field is sufficiently new that one can only list possible candidates for the neural substrates. Regions in the parietal lobe seem heavily implicated, both because of single-cell findings

concerning multimodal interactions that subserve the representation of space (e.g. [44••]) and because of the clinical deficits of spatial attention seen in patients with parietal lesions [53••], plus the multimodal influences that can be shown to affect these deficits (see e.g. [53••,54,55]).

However, many other brain areas may also be implicated in addition to the parietal lobe (e.g. basal ganglia, putamen, premotor cortex, and frontal lobe), given recent clinical and physiological findings. Subcortical structures such as the superior colliculus are known to play a role in the crossmodal control of exogenous overt orienting [42], and may similarly be involved in covert crossmodal orienting as well [17•]. Stein and colleagues (see [56,57••]) have long been pioneers in the study of collicular contributions to crossmodal integration for spatial attention, and their recent work has revealed the crucial role that cortical inputs play in determining crossmodal interactions within the colliculus. Clearly then, the neural basis of crossmodal integration for spatial attention probably involves a diffuse and complex network, which may best be understood by combining functional psychological studies, such as those emphasised here, together with all of the other methods (i.e. neuroimaging, single-cell recording, lesion studies, and modelling [58]), in a convergent manner.

Conclusions

The study of crossmodal selective attention is in its infancy, when compared with the vast body of previous attention research that has only considered single modalities in isolation. Nevertheless, recent research on multimodal issues already shows that crossmodal links in attention are substantial and numerous. There is no single answer to the general question of how attention is coordinated across modalities. Instead, the exact nature of the crossmodal links seems to depend on the particular type of attention involved (e.g. covert versus overt; endogenous versus exogenous) and on the particular modalities concerned. Nevertheless, some generalisations can already be made. Shifts of covert attention in one modality tend to be accompanied by corresponding shifts in other modalities, with just a few exceptions. The correspondence between the modalities in the direction of attention with respect to external space is largely maintained across changes in posture, even when these realign receptors for the different senses. Some crossmodal integration can apparently arise before attentional selection is completed, and this contributes to construction of the representational space(s) in which attention is directed. Finally, crossmodal studies of attention seem a particularly fruitful topic for interdisciplinary exchange, as recent developments in the neuroscience of spatial representation in the brain may be closely related to the psychology of crossmodal attention.

Acknowledgements

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- of special interest
- of outstanding interest

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An extensive review of previous studies that attempted to measure the effects of attending to a particular sensory modality. The authors highlight the numerous confounds inherent in most previous studies. They then present modified cuing paradigms, which demonstrate significant behavioural effects of attending to audition versus vision without these previous confounds.

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Behavioural measures of sensory threshold show that people can detect increments or decrements in auditory and visual pedestal stimuli without a divided-attention cost (as compared with attending to just one modality), but that discrimination of any such change (e.g. as an increment versus decrement) does produce costs of dividing attention between modalities.

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