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Responding to sounds from unseen locations: Crossmodal attentional orienting in response to sounds presented from the rear

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ABSTRACT

To date, most of the research on spatial attention has focused on probing people’s responses to stimuli presented in frontal space. That is, few researchers have attempted to assess what happens in the space that is currently unseen (essentially rear space). In a sense, then, “out of sight” is, very much, “out of mind.” In this review, we highlight what is presently known about the perception and processing of sensory stimuli (focusing on sounds) whose source isn’t currently visible. We briefly summarize known differences in the localizability of sounds presented from different locations in 3-D space, and discuss the consequences for the crossmodal attentional and multisensory perceptual interactions taking place in various regions of space. The latest research now clearly shows that the kinds of crossmodal interactions that take place in rear space are very often different in kind from those that have been documented in frontal space. Developing a better understanding of how people respond to unseen sound sources in naturalistic environments by integrating findings emerging from multiple fields of research will likely lead to the design of better multisensory warning signals in the future. This review highlights the need for neuroscientists interested in spatial attention to spend more time researching what happens (in terms of the covert and overt crossmodal orienting of attention) in rear space.

Introduction

People tend to focus their visual attention in a fairly narrow region of frontal space. That is, they generally concentrate on what is happening in the space that they can see in front of them, and that they will normally move toward (see Previc, 1998, 2000, for reviews; see also Moeller et al., 2016). To date, auditory spatial attention research (no matter whether it be set in a unisensory or crossmodal context) and work on multisensory perception have largely focused on the restricted region of frontal space (see, for example, McDonald & Ward, 1999; Mondor & Zatorre, 1995; Spence & Driver, 1994, for unimodal auditory research, and Spence & Driver, 1997, for audiovisual crossmodal spatial cuing studies, respectively). Meanwhile, many other researchers have focused instead on the somewhat unnatural situation of headphone (i.e., monaural or binaural) presentation, a situation that results in sounds being perceived as originating from inside the head (e.g., see Scharf, 1998, for a review). That said, head-related transfer functions can be used to filter sounds to reproduce signals as if originating from locations in the free-field (e.g., Wenzel, 1992; see Shilling & Shinn-Cunningham, 2002, for a review).

In contrast to research on spatial attention, the literature on auditory localization has often assessed performance in response to sounds presented from the rear in both humans and other species (e.g., Carlile et al., 1997; Makous & Middlebrooks, 1990; Wightman & Kistler, 1989). A number of researchers have focused explicitly on trying to understand the challenges associated with front/back and up/down localization in humans (e.g., Hartmann & Rakerd, 1993; Hofman & Van Opstal, 1998; Macpherson & Middlebrooks, 2000; Zhang & Hartmann, 2010). Similar questions relating to the spatial tuning of auditory neurons have also been addressed in both anaesthetized cats and ferrets (e.g., Middlebrooks et al., 1994, 1998; Mrsic-Flogel et al., 2005; Reale et al., 2000, 2003; Schnupp et al., 2001) and in unanaesthetized cats (Lee & Middlebrooks, 2011, 2013; Mickey & Middlebrooks, 2003).

Much less frequently have *attention* researchers addressed the question of whether the presentation of auditory stimuli from the rear – specifically, from the space that falls outside of the current field-of-view (i.e., behind the head, and typically behind the body too) – will modulate a participant’s spatial attention or multisensory perception more generally (see Figure 1). One of the few exceptions here comes from Spence and Driver (1994, Experiment 1). These researchers presented spatially nonpredictive auditory cues from 90° to either side of central fixation, while auditory targets (requiring a front/back speeded discrimination response) were presented from one of four loudspeakers situated 45° and 135° to either side of fixation. Elsewhere, Spence et al. (2000) also had their participants attend to a voice presented from a loudspeaker placed directly behind their head. However, the relevant point for present purposes is that in neither of these studies was the researchers' interest really in the representation of sounds in rear space.

A question that one might want to ask at this point, then, is why it is that rear auditory space has been neglected by those working in the field of attention research (if not auditory localization) for so long (see Spence & Driver, 2004). Who knows, perhaps it is because the space behind us tends to fall outside of our conscious awareness, given that we all, in some sense, 'see' forward; Arnold et al., 2016; Krech & Crutchfield, 1958)? As we will see below, though, this neglect (from researchers interested in attention) is unfortunate given that there are some interesting questions to be addressed around how the map of rear auditory space is constructed, given vision's important role in calibrating spatial hearing in frontal space.

Few researchers interested in the topic of crossmodal spatial attention have presented sounds from behind their participants (note that the same criticism doesn't apply to those working on auditory localization). Perhaps the reason for this neglect reflects nothing more prosaic than practical/methodological issues. Alternatively, however, one might worry that there is an implicit assumption underpinning much of the research on crossmodal spatial attention that those findings obtained when sound sources are presented in frontal space can safely be generalized to sounds presented from the rear as well. Whatever the most appropriate explanation, the fact remains that one is certainly hard pressed to find any mention of rear sounds in Spence and Driver's (2004) oft-cited edited volume on *Crossmodal Space and Crossmodal Attention*. Empirically evaluating whether the same rules crossmodal spatial orienting apply in both front and rear space becomes especially important for those applications where warning signals may need to be presented from behind an observer's (or should that be listener's) head.

Unique to the auditory modality is the fact that sound sources potentially provide continuous spatial information from the three-dimensional (3-D) space that surrounds us (Perrott, 1993). Sounds, after all, typically alert us to those events that we fail to notice visually (such as a predator approaching stealthily from the rear; see Heffner & Heffner, 1992a, b). Similarly, nowadays, when biking or driving a car, we often hear vehicles approaching from the rear and use that information to determine on which side they will pass us. The benefit of being made aware of events in rear space (even if we can’t see them) becomes all the more apparent when thinking about the electric scooters that have become an increasingly common presence in many cities in recent years. Haven’t many of us had the startling experience of pizza delivery drivers sometimes suddenly appearing next to us in traffic without the scooter’s engine having provided any auditory cue about their presence. No wonder, then, that many people have been worrying about the potential dangers of silent cars for other road users. Indeed, according to European Union regulations, all electric vehicles will have to make some kind of noise by 2021 (see “Electric Cars,” 2014; Petiot et al., 2013).

One of the most important potential application domains, then, for spatial attention research in rear space is in the design of auditory (and/or possibly tactile/haptic) signals. Such signals are often designed to alert drivers to the presence of a vehicle situated in their blind spot, say, or elsewhere in the unseen space that lies behind them (e.g., Chun et al., 2013; Ho & Spence, 2005; Ho et al., 2006; Lee et al., 2004; McKeown & Isherwood, 2007). Intuitively, based on the evidence highlighting the existence of robust crossmodal links in spatial attention (Baldwin et al., 2012; see Spence & Driver, 2004, for a review), one might simply propose that auditory (or tactile) cues should be presented from the direction of the vehicle in the blind spot in order to warn the driver of an object/event that they might otherwise be unaware of, for example. In fact, a number of commentators have already suggested that rear auditory cues should be used in cars for just this purpose (e.g., Ferris & Sarter, 2008; Ho & Spence, 2005, 2008, 2009; Spence & Ho, 2012). However, as we will see below, the latest laboratory evidence suggests that things might not always be quite so simple, given the way in which we tend to respond crossmodally to those sounds whose source is situated behind us.

In the sections that follow, we discuss those studies of spatial hearing, crossmodal spatial attention, and other multisensory interactions that have involved sounds presented from rear space. Often, the findings are compared to what goes on in frontal space. Our goal here is to highlight how the perception of, and more importantly the orienting response toward, auditory and multisensory stimuli from the rear is actually often quite different, both qualitatively and quantitatively, from what happens in frontal space. And, given that (as we have just seen) an awareness of what is going on behind us can play an important role in everyday activities such as safe driving, we would like to encourage more attention/perception research community to broaden their horizons (as it were) and consider the perception of, and responses to, stimuli in rear space in their research. At the same time, though, it is important to recognize the many challenges that are associated with trying to extend one’s research from the lab to the real world (see Spence & Ho, 2015, for a review). Ultimately, we will conclude that the perception of, and responses toward, auditory stimuli in rear space differs much from what is seen in frontal space, and therefore has important consequences for the design of auditory (and multisensory) warning signals (e.g., as increasingly used in vehicles).

Localizing sounds in 3-D space: Mechanisms and systematic errors/biases

When thinking about the contribution that our ability to localize sounds presented from the rear makes to spatial orienting, it is important to consider the many errors/biases that have been identified in our judgment of the source of sounds presented in 3-D space (i.e., 360° in azimuth and elevation; see Carlile et al., 1997). For instance, differences in the localizability of sounds presented in various regions of 3-D space may be expected to affect how precisely attention is focused spatially. That is, harder-to-localize sounds may potentially lead to a broader spread of exogenous spatial attention, while at the same time giving rise to less perceptual facilitation at any given location (see Spence et al., 2004, for a discussion). Similarly, any difficulties in correctly localizing auditory stimuli may also affect the various multisensory behavioral enhancement effects that have been reported in recent years (see Calvert et al., 2004; though see also Spence, 2013).

Localizing sounds in the horizontal plane involves the use of information from binaural cues, including interaural level and time differences (ILDs and ITDs, respectively; Blauert, 1997; Grothe et al., 2010; Middlebrooks & Green, 1991; Rayleigh, 1907; Schnupp et al., 2011). Binaural cues are encoded in the superior olivary complex (SOC), which then projects primarily to the inferior colliculus (IC; Yin, 2002, for a review). However, binaural cues mostly provide information about the likely lateral location of a sound source (though see Perrott & Saberi, 1990). Sounds originating from a hypothetical cone centred on the interaural axis (known as the *cone of confusion*; Shinn-Cunningham et al., 2000) exhibit near-identical ILDs and ITDs. Hence, based on binaural cues, it is only possible to specify the shape of the cone of confusion from which a sound may have originated.

Other than binaural cues, the spectral cues, generated by the external ear (pinna; see Butler, 1975, for a review) as well as the head and the torso (Algazi et al., 2001), are regarded as providing some of the most salient information concerning sound localization (see Wightman

& Kistler, 1997). Spectral cues are crucial for sound localization on the vertical plane and resolving front-back ambiguity (Ovcharenko et al., 2007; Slattery & Middlebrooks, 1994; Talagala et al., 2014; Wenzel et al., 1993; see also Van Wanrooij & Van Opstal, 2005). The peaks and dips in the spectrum (i.e., intensity as a function of the frequency response) systematically shift as the sound source location changes (Mehrgardt & Mellert, 1977; Musicant et al., 1990; see Middlebrooks & Green, 1991, for a review). The pinnae are known to modulate sound amplitude or gain in the frequency range from 3-4kHz and above, and the head diffraction and torso reflections also influence the spectrum change that is observed, particularly for frequencies lower than 3 kHz (Algazi et al., 2001). Spectral cues between 4-16kHz are essential for sound localization with broadband noises (Langendijk & Bronkhorst, 2002; see also Butler & Humanski, 1992; Hebrank & Wright, 1974; Musicant et al., 1990), although the low frequency spectrum below 2kHz is also particularly important as far as the resolution of front-back ambiguities is concerned (Asano et al., 1990; see also Musicant & Butler, 1984). Two of the most important brain regions processing spectral cues are the inferior colliculus (IC; Davis et al., 2003; see also Davis, 2005, for a review) and the auditory cortex (Zatorre & Belin, 2001; Schreiner et al., 2011, for a review).

It turns out that monaural spectral cues, originating from the spectral filtering of sound by the pinnae, head, and torso (e.g., Asano et al., 1990; Parise et al., 2014), are absolutely crucial for the auditory system when it comes to determining whether sounds originate from the front or rear, as well as their elevation (Burger, 1958; Butler & Planert, 1976; Middlebrooks & Green, 1991; Ovcharenko et al., 2007; Slattery & Middlebrooks, 1994; Talagala et al., 2014; Van Wanrooij & Van Opstal, 2005; Wenzel et al., 1993). Resolution of any front-back ambiguity in the localization of a sound source can also be achieved by the movement (e.g., rotation) of the listener's head and/or the sound source (Wallach, 1940; Wightman & Kistler, 1999). Perhaps unsurprisingly, front-back confusions in the localization of sound sources occur more frequently for those stimuli that contain only a limited range of frequencies (e.g., sinusoids or narrowband noise) rather than broadband noise (Butler, 1986; see Middlebrooks & Green, 1991, for a review). Studies of absolute auditory localization abilities in the vertical plane have shown that performance is nearly as accurate as in the horizontal plane (e.g., Carlile et al., 1997; Makous & Middlebrooks, 1981; Parise et al., 2014; though see also Grusser, 1983; Parise et al., 2012, 2013, for somewhat worse performance under a subset of conditions).

Reflections can aid determining the distance of a sound source in naturalistic enclosed environments, such as represented by the typical experimental laboratory (see Bronkhorst &

Houtgast, 1999). The ratio between the direct and the reverberant energy of a sound provides a cue to its distance (i.e. direct-to-reverberant ratio). That said, it has also been reported that people sometimes find it surprisingly difficult to localize the source of sounds that have been presented within particularly reverberant environments, such as inside a car (see Fitch et al., 2007). Fitch et al. had their participants verbally report the location from which an auditory signal had been presented. Eight equispaced sound locations (delivered using an array of four loudspeakers) were presented around the participants (N = 32) who were seated inside a car. Surprisingly, however, the mean accuracy of auditory discrimination responses was a mere 32% (with chance level performance coming in at 12.5%). This contrasted with 84% correct when the participants had to discriminate the location of one of eight vibrotactile stimulators situated in the base of their seat. Sound localization acuity can differ very dramatically, then, depending on the environment in which listeners are tested.

It is perhaps also worth noting here that the surprisingly poor auditory localization performance documented in Fitch et al.'s (2007) study occurred despite the fact that the participants did not have any other task to perform in this study. Such poor localization performance does not necessarily mesh with the sense that we know where the voice of the back-seat passenger is coming from while we drive. However, it is important to bear in mind that the latter might be more a matter of 'knowing' where our passenger's voices originate from, rather than necessarily directly perceiving the source location. Of course, spatial ventriloquism might also have a role to play here (e.g., Alais & Burr, 2004; Charbonneau et al., 2013; Jackson, 1953).

On the multisensory calibration of spatial hearing

Those of us with normal vision are provided with high spatial resolution visual input that can be used to help calibrate our spatial hearing in frontal space (Brainard & Knudsen, 1993; King, 2009; Münte et al., 2001; Röder et al., 1999). Knowing where a sound comes from requires the calibration of auditory input based on its physical location. Specifically, when it comes to horizontal sound localization, ILDs and ITDs need to be associated with physical spatial locations (Brainard & Knudsen, 1993; King, 2009; Knudsen, 2002). Given the high spatial resolution of the visual modality, this sense is an ideal candidate when it comes to calibrating spatial hearing, at least in frontal space (King, 2004).

To date, many studies have shown that vision naturally guides the (re-)calibration of spatial hearing. The dominance of vision in recalibrating auditory spatial representations has, for example, been repeatedly demonstrated in experiments that have investigated the spatial ventriloquist aftereffect (Bertelson et al., 2006; Canon, 1970; Frissen et al., 2003, 2005; Recanzone, 1998; Zwiers et al., 2003). That is, after multiple exposures to sound-light pairs presented simultaneously from different locations (with, say, the sound always presented from 5° to the left of the light), sound localization (even in the absence of a visual stimulus) shifts in the direction of the visual stimulus. The existence of such an aftereffect has been taken to show that spatial hearing is constantly being updated in order to resolve any spatial conflict that may be detected between auditory and visual sources that belong together.

A dominant model in the literature regarding multisensory integration of spatial locations is the maximum likelihood estimation account of optimal cue integration (e.g., Alais & Burr, 2004; Ernst & Banks, 2002). According to the account, the multisensory estimate represents the average of the cues weighted by the inverse of the reliability of the individual sensory estimates. Interestingly, though, it is the accuracy, rather than the reliability, of the individual sensory estimates that determines unsupervised recalibration (Zaidel et al., 2011; see Zaidel et al., 2013, for more on the notion of supervised recalibration).

A conflict between the senses is also sometimes introduced experimentally by plugging a participant’s ear to simulate acute asymmetrical hearing loss. This generally results in a shift in the perceived location of a sound source toward the unplugged ear (Slattery & Middlebrooks, 1994), thus creating a conflict between the senses. After multisensory exposure to spatially and temporally aligned audiovisual stimuli, though, the accuracy of spatial hearing is typically improved under such conditions, indicating that recalibration has taken place (e.g., Hofman et al., 1998; Strelnikov et al., 2011; see Mendonça, 2014, for a review).

Calibrating the location of sound sources situated to the rear

At this point, the more interesting question, at least in the context of the present review, concerns what happens when vision is not available to help calibrate spatial hearing. How exactly is the spatial calibration of sound sources achieved in the space that cannot be seen? This might either be because an individual is blind or, for sighted individuals, because sounds originate from the space they normally cannot see (i.e., because the sound source is situated behind their head). Here it has been suggested that head movements may play an important role in localizing and calibrating rear auditory spatial perception (Hofman et al., 1998; Perret & Noble, 1997; Wallach, 1940). So, for example, take the following from Hofman et al. (1998, p. 420), when describing the results of one of their studies: *“active head movements may also have contributed to the calibration of the auditory localization system, especially for those spatial regions where vision has a poor resolution (that is, in the far retinal periphery) or is even absent (for example, for rear stimulus positions and in darkness).”* (see also Brimijoin & Akeroyd, 2012).

Additionally, or alternatively, however, the calibration of spatial hearing for sounds originating from the rear might also be achieved by applying the same calibration of auditory space obtained in frontal space (i.e., relating ILDs and ITDs to spatial locations) to rear space. If this were to be the case, the accuracy and precision of sound localization would only be expected to be limited by the physical changes to sounds when they originate from the rear, rather than the front. As mentioned earlier, the spectral content of sounds change given that the ears are directed in a frontal direction (e.g., van Wanrooij & Van Opstal, 2005). This change in the acoustic spectrum of sounds presented from the rear may well affect the accuracy of sound localization.

In recent years, it has been shown that audio-*motor* feedback helps calibrate spatial hearing for unseen sound sources positioned in frontal space (Finocchietti et al., 2015, 2017). Finocchietti et al. (2017) had a group of blindfolded sighted participants as well as a group of congenitally blind participants localize 500Hz, 180bpm intermittent sounds in frontal space before, and then again after, audio-motor training. In this case, training consisted of the participants moving the speaker playing the sound with the**ir** hand in order to explore the space around their body. A control group received no such training. Absolute sound localization performance was worse in the congenitally blind participants than in the blindfolded sighted participants prior to training (that is, the localization error was larger). Intriguingly, however, sound localization performance improved dramatically in the congenitally blind participants following training. Although Finocchietti et al.’s results indicate that audio-motor feedback can be used to recalibrate spatial hearing in frontal space, this is presumably an unlikely candidate for the calibration of spatial hearing in either *far* frontal space or *rear* space (either near or far). This is because we mainly move our limbs around within a limited distance of the body in front of us. That is, we have only limited degrees of movement behind us (cf. Kóbor et al., 2006, for differences in tactile discrimination performance between front and rear space).

More relevant here concerning the calibration of rear auditory space are findings reported by Gori et al. (2014). Specifically, these researchers measured auditory spatial bisection thresholds in blindfolded sighted participants before and after audio-tactile training. There was a total of two feedback training sessions in between three threshold measurements and there were three training groups in their study. One group received tactile spatially congruent feedback presented on the forearm 200ms after the presentation of a horizontal auditory sequence (originating from loudspeakers placed in front of them). Another group received verbal feedback regarding the speaker sequence, while a third group received no feedback at all during the auditory stimulation. The auditory sequence consisted of three sounds presented from left to right consecutively. The first and third sounds were presented from fixed positions, separated by a visual angle of 35°, whereas the second sound was presented in-between. In the bisection threshold task, the participants reported whether the second sound was closer to the first or third sound.

Only the provision of tactile feedback led to improved auditory spatial localization performance, thus hinting at the occurrence of audio-tactile recalibration. In a control training phase, Gori et al.’s (2014) participants were rotated by 180°, thus making the tactile feedback that they received on their arm now spatially and directionally incongruent with regard to the sound sequences that were presented from behind them (e.g., auditory left to right, and tactile right to left). Perhaps unsurprisingly, no improvement in sound localization performance was documented under such conditions. However, in another group, the participants were rotated 180° and the direction of the tactile sequence reversed, such that the tactile feedback on the arm was again directionally congruent with the sound sequence during the training phase. Under such conditions, the spatial bisection threshold performance for sounds presented from the rear improved, albeit less than when the loudspeakers (and tactile feedback training) were presented from in front of the participants. These results therefore suggest that tactile spatial information can recalibrate spatial hearing, even when sounds are presented from the rear (and tactile stimulation is provided from in front of the participant). Presumably visual information should be able to serve a similar function as touch in Gori et al.’s study (of calibrating spatial hearing in rear space) given the typically higher resolution of the visual system.

Potentially relevant regarding the calibration of spatial hearing in rear space (both in the horizontal and depth dimensions), several studies have shown that tactile stimuli are integrated with sounds that originate from sources placed directly behind the head, but not with sounds that are presented from further away (e.g., see Occelli et al., 2011; Van der Stoep et al., 2015a, for reviews). So, to the extent that somatosensation plays a role in the calibration of spatial hearing in rear space, one could imagine that this is most likely limited to those sounds originating from close to the body, or else those sound sources that approach the body. Such a distinction would potentially allow for a binary assessment of whether a sound source is close to, or far from, the back of the head (i.e., a crude calibration of auditory distance perception in the rear; see Graziano et al., 1999). Sound localization in rear space (in both the horizontal and vertical dimensions) could presumably be calibrated based on somatosensory stimulation as well, as a function of where on the body tactile stimulation is experienced during the presentation of sound in rear space.

Interim summary

To summarize what we have seen thus far. We have reviewed the literature on the localization of sound sources in 3-D space, and have identified some of the systematic biases/errors in sound location that has been documented across 3-D space (see Carlile et al., 1997, for a summary of the literature on errors in sound localization). We have also highlighted some of the ways the presumed location of sounds from the rear may be calibrated. As such, we are now in a much better position to look at the literature concerning the spatial cuing of attention following the presentation of rear auditory cues.

Directing spatial attention to the rear

Using spatially-nonpredictive auditory cues to draw attention to the rear exogenously

Over the last two decades or so, a number of studies have demonstrated that the presentation of auditory cues, even those that are spatially-nonpredictive with regard to the likely location of an upcoming target, typically lead to a short-lasting shift of spatial attention to the cued region of space (e.g., see Spence, 2001, 2010, for reviews). Such auditory cues have been repeatedly shown to facilitate the processing of auditory, visual, and tactile stimuli subsequently presented from the cued location for a short period after the presentation of the cue (e.g., Spence & Driver, 1994, 1997, Spence et al., 1998). At longer cue-target intervals, though, these facilitatory effects often reverse to become a longer-lasting inhibitory aftereffect, known as ‘Inhibition of Return’, at least in simple detection tasks (see Klein, 2000; Spence et al., 2000). Crossmodal exogenous spatial cuing effects tend to be focused fairly narrowly around the location of the cue (Lee & Spence, 2017; see Spence et al., 2004, for a review). However, given what we have seen so far, it should come as no surprise to find that the majority of the spatial cuing studies that have been published to date have involved the presentation of sounds from a fairly narrow region of visible frontal space.

At Oxford University’s Crossmodal Research Laboratory, though, we have started to investigate the spatial distribution of crossmodal exogenous spatial cuing effects following the presentation of sounds originating from behind the head (see Figure 2, for a bird’s-eye view of the experimental set-up used in Lee and Spence’s, 2015, study). Lee and Spence used a variant of the orthogonal spatial cuing paradigm (see Spence & Driver, 1994, 1997) in which a spatially-nonpredictive auditory cue was presented to either side of central fixation prior to the presentation of a visual target requiring participants to make a speeded elevation discrimination response. The visual target consisted of the brief illumination of an LED on either the left or right. Note that there were two LEDs on each side, one placed 80 cm (33.7°) directly above the other. The participant’s task is orthogonal in the sense that the direction in which the cue is presented (left vs. right) is orthogonal to the direction in which participants need to discriminate (up vs. down), thus ruling out a simple response bias explanation of any cuing effect obtained. Note that such an alternative explanation has plagued the interpretation of many previous studies of crossmodal attentional cuing (see Spence & McDonald, 2004 for an overview).

The results of Lee and Spence’s (2015) study revealed that responses to frontal visual targets were not only faster, but also somewhat more accurate, when an auditory cue (i.e., either a pure tone or a burst of white noise) was presented from the same, rather than the opposite, hemifield (this is in line with prior studies; e.g., Spence & Driver, 1997). Note that this basic same-side spatial cuing effect fits with the literature showing that auditory cortical neurons tend to have hemifield receptive fields (RFs) that tend to fill the space contralateral to the cortical neuron. Both psychophysical data in humans (Boehnke & Phillips, 1999), and the latest neuroimaging research in awake and anaesthetized macaque monkeys (Ortiz-Rios et al., 2017), suggests that the location of sound sources appear represented by opponent activity of two (or a small number) of cortical neuron populations having broad, hemifield, spatial RFs. Nevertheless, the more surprising result to emerge from this study was that this cuing effect was observed no matter whether the spatially-nonpredictive auditory cues were presented from the front *or* from the rear. That is, rear auditory cues facilitated frontal target discrimination performance just as much as auditory cues presented from exactly the same lateral eccentricity as the target. The latter result has been referred to as the rear-to-front crossmodal spatial cuing effect. Importantly, this pattern of results was obtained despite the fact that the rear loudspeakers were separated from the frontal visual targets by an angular separation of 90°.

A separate sound location discrimination test confirmed that the rear-to-front crossmodal spatial cuing effect could not simply be attributed to participants being confused about whether the auditory cues had come from the front or rear. In fact, they were able to correctly discriminate the front-back locations of the auditory stimuli, with an accuracy of 92% and 88% for sounds presented from front and rear space, respectively. Of course, the participant's attention would likely have been directed endogenously to the front, given that that is where all of the targets were presented. However, the evidence suggests no effect of spatial attention on the ventriloquism effect (see Bertelson et al., 2000; Spence & Driver, 2004). And, by contrast, the ventriloquism effect has been shown to influence the exogenous (i.e., voluntary) allocation of spatial attention (see Spence & Driver, 2000; Vroomen, Bertelson, & de Gelder, 2001). Relevant here, though, the presence of a stimulus onset asynchrony (SOA; of 100, 200, or 700ms) between the presentation of the cue and that of the visual target will likely also have reduced the magnitude of any spatial ventriloquism effects (see Slutsky & Recanzone, 2001; Wallace et al., 2004). The key point to bear in mind, though, is that Lee and Spence (2015) were able to rule out any kind of front-back confusion as a potential explanation for the rear-to-front crossmodal spatial cuing effect.

We have now replicated the rear-to-front crossmodal spatial cuing effect in a separate study (Lee & Spence, unpublished) thus suggesting that the phenomenon is reasonably robust. In particular, in our replication study, the visual targets (i.e., white circles) were now projected onto a sound-transparent cloth screen, situated in front of the loudspeakers (see Figure 3). Auditory cues consisted of a 50ms white noise burst presented at 80dBA, as measured from directly in front of the loudspeaker. Following the onset of an auditory cue in each trial, a visual target was presented on the screen for 50ms after one of the four stimulus onset asynchronies (SOAs: 100, 200, 400, or 700ms). Once again, the presentation of the taskirrelevant peripheral white noise auditory cue was shown to lead to faster responses to frontal visual targets on the same, rather than opposite, side of fixation, regardless of whether the cues were presented from the front or rear.

The magnitude of the crossmodal spatial cuing effect was smaller than that reported in Lee and Spence (2015; 5ms as compared to 11ms). It should, however, be noted that the lateral separation between the center of a visual target on one side and the fixation point was only 9.2° in this study, as compared to 45° in Lee and Spence's (2015) previous study. Therefore, the small magnitude of the crossmodal spatial cuing effect reported in this replication study might be attributable to the close proximity of the two cue locations (at the front and at the rear; see Carrasco et al., 1995; Carrasco & Frieder, 1997; Lee & Spence, 2017, on eccentricity effects).

Accounting for the rear-to-front crossmodal cuing effect

The evidence demonstrates the existence of a rear-to-front crossmodal spatial cuing effect. At first glance, this would appear to suggest that simply presenting an auditory warning signal in the direction of a vehicle (e.g., to alert the driver to the presence of an unseen vehicle in the blind spot, say) may not necessarily lead to the exogenous orienting of a driver's attention to the cued direction/region of space, as might have been expected based on the prior attentional cuing research that has been conducted in frontal space. But how should such an unexpected cuing effect be explained? An analysis of the spatial RF properties of auditory and visual neurons in the superior colliculus (SC), a midbrain structure known to be involved in overt and covert orienting of spatial attention (e.g., Ignashchenkova, Dicke, Haarmeier, & Their, 2004; Kustov & Robinson, 1996; Moore, Armstrong, & Fallah, 2003; Spence, 2014), might help to provide an answer here. Indeed, the role of the spatial colocation of the cue and target stimuli in the crossmodal spatial cuing effect has often been explained in terms of the response properties of the multisensory neurons in the SC (e.g., Lee & Spence, 2017; Leo, Bertini, di Pellegrino, & Ladavas, 2008; Spence, 2013; Spence & Driver, 1997).

The multiple layers of the SC are divided into superficial and deep layers (see Wallace et al., 1996), with the neurons in the superficial layers of this midbrain structure responsive exclusively to visual stimuli (Lovejoy & Krauzlis, 2010). By contrast, neurons in the deep layers respond to auditory and somatosensory stimuli as well. In the animal model (i.e., testing on anesthetised cats), the size of the RFs of multisensory neurons in the rostral SC (responsive to the frontal/nasal space) are considerably smaller than those found in the caudal (responsive to the peripheral/temporal space) SC (Kadunce et al., 2001). In the rostral SC, visual RFs range from less than 10-40° of visual angle in diameter, while auditory RFs range from 20-60° in diameter. However, in the caudal SC, these figures jump to 40-100° and 60-135° for visual and auditory stimuli, respectively. Given the size of auditory RFs in the caudal SC, auditory RFs often extend into rear space, well beyond the limits of the visual RF (see also Kadunce et al., 1997; Middlebrooks & Knudsen, 1984; Meredith & Stein, 1996; Wallace et al., 1996). As such, an auditory cue presented in the rear-left position in Lee and Spence's (2015) study (e.g., 135° in azimuth from central fixation), for instance, might well still fall within the RF of an audiovisual SC neuron that has a visual RF that is responsive to visual stimuli in the front-left region of space.

At this point, though, a few notes of caution are in order. One is that the single-cell neurophysiological data based on anaesthetized cats can obviously only provide a hypothetical explanation of the crossmodal spatial cuing effects from the rear auditory cues based on awake human participants (see also Populin & Yin, 1998, 2002). However, that said, similar properties, such as RF alignment and multisensory integration, have, on occasion, also been reported in the monkey SC (see Wallace et al., 1996). We therefore believe that the neurophysiological perspective concerning the multisensory interactions taking place in the SC that underlie both covert and overt attention shifts provides a viable account for the spatially-nonspecific audiovisual cuing effect reported by Lee and Spence (2015).

Second, it needs to be noted that while the SC may well be a critical structure for multisensory interactions (see Stein & Meredith, 1993, for a review), it is certainly not a crucial neural structure for sound localization. Intriguingly, lesioning the SC in the cat has been shown to compromise unimodal visual and auditory orientating for a period of only 2-5 weeks. Following the recovery period, post-lesioned cats appear to exhibit relatively normal orientation behaviors toward auditory stimuli (e.g., Burnett et al., 2004; see also Thompson & Masterton, 1978; and Wagner, 1993, for similar results after lesions in the external nucleus of the inferior colliculus [ICx] or the optic tectum [OT]). Such findings show that sound localization must (or at least can) be performed elsewhere than the SC. Candidate structures here include the IC and/or the auditory cortex (see Chabot et al., 2013; Lomber et al., 2007, for the neural network between the SC and the auditory cortex). Indeed, cortical lesions have been shown to produce clear deficits in volitional sound localization (e.g., Heffner & Heffner, 1990; Heffner & Masterton, 1975; Malhorta et al., 2004, 2008; Wagner, 1993), and there is a sizeable literature on cortical representation of azimuthal sound-source location (e.g., Furukawa & Middlebrooks, 2002; Middlebrooks et al., 1994; see Middlebrooks, 2014, for a review).

That said, it is also worth bearing in mind that the amplitude of the Binaural Interaction Component (BIC) of the Auditory Brainstem Response (ABR) relates directly to the perceived location of sounds (see Laumen et al., 2016, for a review). Furthermore, given that ILD and ITD are calculated in nuclei in the brainstem (MSO and LSO; see Celesia, 2015), and given the fact that the IC contains a map of auditory space, it would seem reasonable to suggest that the rapid orienting to sounds is mainly driven by brainstem activity. The subcortical structures are clearly not independent from cortical processing, but they are largely responsible for reflexive crossmodal orienting.

Exogenously directing attention to rear visual events seen in the rearview mirror

Whatever the neural substrates of auditory localization and orienting, it is interesting to note that a rather different conclusion to that emerging from Lee and Spence's (2015, unpublished) studies has, though, emerged from those studies in which the sound of a car horn has been presented from directly behind (or in front of) a driver (e.g., Ho & Spence, 2005, 2008, 2009). Such warning signals have been used to alert the driver to an approaching car on the road behind them, visible via the rearview mirror. Meanwhile, a car horn sound was presented from the front (or behind) to signal the rapid deceleration of a vehicle seen on the road ahead of the driver. (Though note that for methodological reasons, the location of the car horn sound in these studies was often made non-predictive with regard to the location of the target car).

The results of a number of such spatial cuing studies that have been conducted over the last decade or so have demonstrated that the presence of such semantically-meaningful (or iconic; Gaver, 1986, 1993a, b) auditory cues can facilitate people's responses to visual targets presented from the cued region of rear space as compared to those presented from the opposite direction (Ho & Spence, 2005, 2008; see also Ho et al., 2005, 2006, for similar results). The existence of such robust crossmodal exogenous spatial cuing effects suggest that rear sounds do indeed facilitate visual discrimination of rear visual events seen via the rearview mirror. Therefore, Ho et al.'s results do, at least at first glance, seem to stand in contrast to Lee and Spence's (2015; unpublished) findings concerning the rear-to-front crossmodal cuing effect. So what exactly could be going on here to explain this discrepancy?

It is important to note that the spatially-nonpredictive auditory cues used in Ho et al.'s studies, while presented from behind the participant/driver, actually facilitated discrimination latencies for visual targets that were seen via mirror reflection from a mirror placed directly in front of the participant. Therefore, it can be argued that, at least from the perspective of the visual system, these targets were, in fact, 'presented' from frontal space. As such, one can question whether the visual attention of the participants was actually directed behind the driver in Ho and colleagues' various simulated driving studies. That said, when the auditory cue was presented from in front of the participant/driver, it facilitated discrimination latencies for visual targets presented from the front more than those seen via the rearview mirror (and originating from the rear). Further evidence that rear auditory events really can be linked to rear visual events, as we will see below, comes from another study (Spence & Driver, unpublished) in which the participants had to direct the auditory (and visual) attention endogenously to the rear in order to try and make out what a speaker was saying.

Endogenously attending to visual events from the rear

One of the few studies to have assessed the consequences of endogenously (i.e., voluntarily) attending to rear space for audiovisual integration was built on Driver and Spence's (1994) audiovisual shadowing studies (see also Spence & Read, 2003). Driver and Spence demonstrated that people found it significantly easier to report what a speaker was saying when the sound of their voice and the sight of the associated lip movements came from the same, rather than different, external position(s). Spence and Driver (unpublished) took this idea to address the question of where best to position a monitor displaying the lip-movements when listening to someone speaking from behind (see Figure 4 for the experimental set-up). The results of the latter study revealed that speech intelligibility was significantly better for relevant auditory speech presented from the front when the lip-movements were presented on the co-located monitor at the front than when viewing the mirror reflection (showing the monitor to the rear). This despite the fact that the visual images projected onto the retina were identical in both cases. The magnitude of this frontal auditory speech advantage was, however, reduced when participants attended to the lip movements presented from behind (and seen via mirror reflection; i.e., the rear monitor image viewed indirectly via the reflection on mirror situated in front). These results therefore demonstrate that audiovisual attention can, in some meaningful sense, be directed endogenously to rear space. Here, it is worth noting that researchers have also used a similar mirror set-up to investigate the role of common spatial origin in visuotactile integration too (see Helbig & Ernst, 2007; Maravita, Spence, Sergent, & Driver, 2002; Sambo & Forster, 2011).

Using spatially-predictive auditory cues to direct attention to the rear endogenously

There is good evidence to show that informative auditory cues can be used to facilitate goal-directed saccades to visual targets in frontal space (e.g., Corneil et al., 2002; Perrott et al., 1991). Furthermore, many published human factors studies have demonstrated that such auditory cues enhance the performance of those interface operators wanting to detect, localize, and/or identify visual targets (e.g., see Bolia et al., 1999; Hancock et al., 2013; McIntire et al., 2010; Perrott et al., 1996; Rudmann & Strybel, 1999; Vu et al., 2006). The presentation of spatially-informative auditory cues facilitate RTs in visual tasks (such as search, detection, or discrimination) by as much as 40% or more without necessarily increasing error rates, compared to performance in the condition from which no cues were provided (Hancock et al., 2013).

Here, though, it is important to note that the presentation of an auditory cue might be informative in one of two ways. Its occurrence might simply alert an interface operator to the presence of a visual event (i.e., without providing any information as to where that visual event is located in space; e.g. Diederich & Colonius, 2008; Los & Schut, 2008; Los & Van der Burg, 2013; Spence & Driver, 1997; Van der Stoep et al. 2015b). Additionally, however, the location of the auditory cue may itself indicate where the relevant visual event can be found. Both types of cue have been shown to facilitate human performance (e.g., Diederich & Colonius, 2008). Furthermore, it should also be noted that the magnitude of spatial cuing effects, no matter whether the cues are informative or not, will likely depend on the eccentricity of the visual targets, with greater cuing effects seen in the periphery (see Lee & Spence, 2017; Perrott et al., 1990).

Importantly, such spatially-correlated (e.g., informative) auditory cues turn out to be more effective in facilitating visual performance when the targets (and hence also the auditory cues) are presented in rear space rather than in the frontal space. For instance, the participants in a study by Perrott et al. (1990) had to discriminate visual letter targets (i.e., “L” or “R”) that were presented randomly in the free-field 0-130° azimuth to either side of central fixation. Note that the participants in this study were allowed to move their heads freely following stimulus onset allowing them to (eventually) see the visual targets that were presented at 130°. The visual targets were presented at the same time as an auditory cue. In the spatially-correlated condition, the auditory and visual stimuli were always presented from the same location on each trial. By contrast, in the spatially-uncorrelated condition, the auditory cue was always presented from directly in front of the participants while a visual target was presented from a random location on each trial. Perhaps unsurprisingly, the results of this early study revealed that the participants responded significantly faster to visual targets in the spatially-correlated condition than in the uncorrelated condition. However, the slightly more intriguing result to emerge from this study was that the magnitude of this crossmodal facilitation effect increased as a function of increasing target eccentricity in the former condition.

Interim summary

Taken together, then, the limited evidence concerning the consequences for crossmodal links in audiovisual attention of presenting sounds from the rear portrays a somewhat complex story. On the one hand, the presentation of spatially-nonpredictive auditory cues from the blind spot lead to an exogenous shift of spatial attention to frontal locations on the same side (Lee & Spence, 2015, and unpublished data). On the other, a number of studies have demonstrated that spatially-nonpredictive car horn sounds, when presented from directly behind a participant in a driving simulator, facilitate people’s responses to visual events occurring at the rear (rather than the front). Furthermore, the results of a shadowing study have also demonstrated that people find it easier to listen to someone speaking from behind them (rather than in front) if simultaneously paying attention to the sight of someone speaking behind them (Driver & Spence, unpublished). On top of that, those studies that have presented spatially co-located (and hence 100% predictive) auditory cues highlight the sometimes dramatic visual search benefits that may ensue when people have to try and localize unseen visual targets (e.g., Perrott et al., 1990).

One possible explanation here as to why sounds from the rear do not always direct a person’s attention toward the location of their source may be that it depends on the context of the behaviour underlying the effect. That is, if targets can appear at any location in 360° then the location of the source of the auditory cue becomes spatially pertinent with regards to the front/rear location of the visual target (e.g., Perrott et al., 1990). However, if visual targets only ever appear in the frontal hemifield, then the position of the source of the auditory cue is no longer spatially predictive with regard to the actual location of the visual target (e.g., as in Lee & Spence’s, 2015, unpublished, studies). Put simply, perhaps we only pay attention to rear space when what is going on there is potentially relevant to our current task demands. This explanation entails a flexible (or context-dependent) system, just as has been proposed previously when trying to explain the conflicting findings regarding the importance of the principle of spatial alignment in multisensory interactions (see Spence, 2013, for a review). One might also be reminded here of the principle of spatial relevance in auditory exogenous spatial cuing (see McDonald & Ward, 1999), which itself bears some similarity to earlier notions around contingent capture of attention (see Folk, Remington, & Johnson, 1992).

Nevertheless, given this continued uncertainty concerning the conditions under which sounds from the rear do/don’t direct a person’s attention toward their source, further research is clearly needed. Addressing this issue will likely also require clarification concerning what exactly it means to say that someone is ‘attending visually to the rear’. Obviously, stimuli that are presented out of the current field-of-view can only be seen via mirror reflection (e.g., Ho & Spence, 2005), video feedback (cf. Tipper et al., 1998, 2001), or else their presence may be inferred by the way in which they illuminate the environment, or the shadows they cast; cf. Pavani & Castiello, 2004; Pavani & Galfano, 2007). To date, two kinds of solutions to the study of human information-processing for stimuli presented in rear space have been used in studies of crossmodal spatial attention. Some studies have having their participants overtly orient to find visual targets that have deliberately been presented out of the current field-of-view (i.e., turn their head, see Ho & Spence, 2009; Perrott et al., 1990). Meanwhile, other studies have presented visual stimuli whose origin is located out of the current field-of-view, but which can be seen via mirror reflection (e.g., Ho & Spence, 2005; Ho et al., 2005, 2006; Spence & Driver, unpublished).

The situation is, though, somewhat simpler when it comes to the case of the audiotactile interactions taking place in front vs. rear space, and it is on that research that we will focus briefly in the final section of our review.

Audiotactile multisensory interactions in rear space

In recent years, there has been a sudden growth of interest in the study of audiotactile interactions in rear space. It turns out that the nature of the interactions between these two spatial senses differs qualitatively, and not just quantitatively, as a function of whether sounds are presented close to, or further away from, the back of the head. The region that is known as near-rear peripersonal space is thought to extend for about 20-60 cm out from the back of the head (see Occelli et al., 2011, for a review). Several studies have demonstrated that multisensory spatial interactions tend to be much more pronounced in this region than when the auditory stimuli (especially when they consist of broadband stimuli like white noise) are presented from further away behind the head or from in front of an observer. While support for the distinction between different regions of rear space initially came from animal neurophysiology (Graziano et al., 1999, 2004), subsequent support has come from a number of sources, including both neuropsychological patient studies (Farnè & Làdavas, 2002) and human psychophysics (e.g., Kitagawa et al., 2005; Occelli et al., 2010; though see also Zampini et al., 2007).

In our own behavioural work here at the Crossmodal Research Laboratory in Oxford, we have demonstrated robust differences in the magnitude of the spatial modulation of unspeeded audiotactile temporal order judgments (Kitagawa et al., 2005, Experiment 1), spatial speeded response compatibility effects (Kitagawa et al., 2005; Experiment 2), and the Colavita effect (Occelli et al., 2010). The latter refers to the phenomenon whereby people fail to respond to one of two simultaneously-presented stimuli perceived via different senses (see Spence et al., 2011, for a review). So, for example, Occelli et al. reported that the presentation of an auditory target sometimes suppressed participants' responses to a simultaneously-presented vibrotactile target. However, this form of sensory dominance was only observed when the sounds were presented from close to the back of the participant's head on the same side as the tactile stimulus that they extinguished. No such crossmodal effects were observed when the auditory targets were presented from frontal space instead.

Meanwhile, Ho and Spence (2009) took Graziano and colleagues' suggestion concerning the existence of a near-rear peripersonal defensive brain circuit and investigated people's speeded head-turning responses in a simulated driving task following the presentation of a near-rear auditory warning signal. The presentation of a burst of white noise from just behind a driver's head gave rise to significantly faster head-turning responses than when the same cue was presented from far frontal locations, or when visual/tactile cues were used to convey the same information (i.e., warning signal) instead. While Ho and Spence's study confounded distance (near/far) with front/back location, other research in this area has clearly demonstrated that it is specifically near-rear auditory cues that are needed to trigger these head-turning effects (see Occelli et al., 2011, for a review). Given their results, Ho and Spence argued that auditory warning signals should be presented in different regions of space depending on the particular behavioural response that was desired from the participant/driver (e.g., head-turning vs. braking to avoid a front-to-rear-end collision, say; see also Spence, 2012, on this theme). Once again, though, the key point to take away from the research that has been reviewed in this section is that people respond in a qualitatively different manner to those sounds that are presented in near-rear peripersonal space than to those sounds that originate from further away (see Van der Stoep et al., 2014, 2015a, 2016a, b, for the effects of stimulus-observer distance and spatial alignment in depth on crossmodal cuing and multisensory integration in front and rear space).

Conclusions

In this review, we have discussed the literature concerning how attention is oriented to sounds (and other stimuli) that happen to be presented from locations falling outside of the current field-of-view. It should be clear, hopefully, that there is now growing evidence to show that qualitatively different patterns of crossmodal interaction can, and often are, observed in the various different regions of space (see Occelli et al., 2011, Van der Stoep et al., 2015a, 2016a for reviews)., One therefore needs to be careful about assuming that the responses to auditory stimuli that have been documented in frontal space will necessarily also be seen with sound sources positioned in rear space instead. While such differences between front and rear space may, in part, be related to differences in the localizability of sound sources (as a function of their positions relative to a listener's head), this does not appear to be the whole story. Rather, based on the emerging neurophysiological literature, it would appear that different brain circuits are responsible for detecting, and responding to, sounds presented in different regions of space (see Graziano et al., 1999, 2004; Ho & Spence, 2009; Occelli et al., 2011; Previc, 1998, 2000). These neural representations appear to have somewhat different response properties, as documented in studies of attentional orienting, overt responding (i.e., head-turning), and multisensory integration. That said, it can be difficult to discriminate between the effects of crossmodal spatial attention and multisensory integration (see McDonald et al., 2001, and Van der Stoep et al., 2015b, on this theme). Intriguingly though, for those who are interested in this distinction, it has recently been suggested that attentional effects may show an asymmetry not present for multisensory integration (see Chen & Spence, 2017, for a review). In the future, therefore, it will be interesting to try and determine the extent to which lateral asymmetries in crossmodal attention vary in rear space in a similar manner as they have been hypothesized to do in frontal space. As such, in the future, applied researchers will need to exercise caution in those real-world situations in which an interface operator's spatial attention needs to be directed to regions of space that they cannot currently see.

Another important point to take from this review is the need for close communication, or at least interconnectedness, between different fields of research. It can be argued that combining insights from audiology, neuroscience, and experimental psychology will be a key to gain a better understanding of the intricate relation between and the relative contributions of the senses to perception in 3-D space. With this review, we hope to have provided the reader with a better understanding of and new insights concerning the perceptual processes and neural mechanisms at play here. As such, moving forward, our hope is that 'out of sight' will no longer imply 'out of mind'.

Abbreviations

SC – Superior Colliculus
RF – Receptive Field
IC – Inferior Colliculus
ICx – External Nucleus of the Inferior Colliculus
OT – Optic Tectum

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REFERENCES

Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology*, **14**, 257-262.

Algazi, V. R., Avendano, C., & Duda, R. O. (2001). Elevation localization and head-related transfer function analysis at low frequencies. *Journal of the Acoustical Society of America*, **109**, 1110-1122.

Arnold, G., Spence, C., & Auvray, M. (2016). Taking someone else's spatial perspective: Natural stance or effortful decentring? *Cognition*, **148**, 27-33.

Asano, F., Suzuki, Y., & Sone, T. (1990). Role of spectral cues in median plane localization. *Journal of the Acoustical Society of America*, **88**, 159-168.

Baldwin, C. L., Spence, C., Bliss, J. P., Brill, J. C., Wogalter, M. S., Mayhorn, C. B., & Ferris, T. K. (2012). Multimodal cueing: The relative benefits of the auditory, visual, and tactile channels in complex environments. *Proceedings of the 56th Human Factors and Ergonomics Society meeting*, **56**, 1431-1435.

Bertelson, P., Frissen, I., Vroomen, J., & De Gelder, B. (2006). The aftereffects of ventriloquism: Patterns of spatial generalization. *Attention, Perception, & Psychophysics*, **68**, 428-436.

Bertelson, P., Vroomen, J., De Gelder, B., & Driver, J. (2000). The ventriloquist effect does not depend on the direction of deliberate visual attention. *Perception & Psychophysics*, **62**, 321-332.

Blauert, J. (1997). *Spatial hearing: The psychophysics of human sound localization*. Cambridge, MA: MIT Press.

Boehnke, S. E., & Phillips, D. P. (1999). Azimuthal tuning of human perceptual channels for sound location. *Journal of the Acoustical Society of America*, **106**, 1948-1955.

Bolia, R. S., D'Angelo, W. R., & McKinley, R. L. (1999). Aurally aided visual search in three-dimensional space. *Human Factors*, **41**, 664-669.

Brainard, M. S., Knudsen E. I. (1993). Experience-dependent plasticity in the inferior colliculus: A site for visual calibration of the neural representation of auditory space in the barn owl. *Journal of Neuroscience*, **13**, 4589-4608.

Brimijoin, W. O., & Akeroyd, M. A. (2012). The role of head movements and signal spectrum in an auditory front/back illusion. *i-Perception*, **3**, 179-182.

Bronkhorst, A. W., & Houtgast, T. (1999). Auditory distance perception in rooms. *Nature*, **397**, 517-520.

Burger, J. F. (1958). Front-back discrimination of the hearing system. *Acustica*, **8,** 301-302.

Burnett, L. R., Stein, B. E., Chaponis, D., & Wallace, M. T. (2004). Superior colliculus lesions preferentially disrupt multisensory orientation. *Neuroscience*, **124**, 535-547.

Butler, R. A. (1975). The influence of the external and middle ear on auditory discriminations. In W. D. Keidel & W. D. Neff (Eds.), *Handbook of sensory physiology* (pp. 247-260). Berlin: Springer-Verlag.

Butler, R. A. (1986). The bandwidth effect on monaural and binaural localization. *Hearing Research*, **21**, 67-73.

Butler, R. A., & Humanski, R. A. (1992). Localization of sound in the vertical plane with and without high-frequency spectral cues. *Perception & Psychophysics*, **52**, 182-186.

Butler, R. A., & Planert, N. (1976). The influence of stimulus bandwidth on localization of sound in space. *Perception & Psychophysics*, **19**, 103-108.

Canon, L. K. (1970). Intermodality inconsistency of input and directed attention as determinants of the nature of adaptation. *Journal of Experimental Psychology*, **84**, 141-147.

Carlile, S., Leong, P., & Hyams, S. (1997). The nature and distribution of errors in sound localization by human listeners. *Hearing Research*, **114**, 179-196.

Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunction searches. *Perception & Psychophysics*, **57**, 1241-1261.

Chabot, N., Mellott, J. G., Hall, A. J., Tichenoff, E. L., & Lomber, S. G. (2013). Cerebral origins of the auditory projection to the superior colliculus of the cat. *Hearing Research*, **300**, 33-45.

Charbonneau, G., Véronneau, M., Boudrias-Fournier, C., Lepore, F., & Collignon, O. (2013). The ventriloquist in periphery: Impact of eccentricity-related reliability on audio-visual localization. *Journal of Vision*, **13(12)**:20, 1-14.

Chen, Y.-C., & Spence, C. (2017). Hemispheric asymmetry: Looking for a novel signature of the modulation of spatial attention in multisensory processing. *Psychonomic Bulletin & Review*, **24**, 690-707.

Chun, J., Lee, I., Park, G., Seo, J., Choi, S., & Han, S. H. (2013). Efficacy of haptic blind spot warnings applied through a steering wheel or a seatbelt. *Transportation Research Part F: Traffic Psychology and Behaviour*, **21**, 231-241.

Celesia, G. G. (2015). Hearing disorders in brainstem lesions. *Handbook of Clinical Neurology*, **129**, 509-536.

Corneil, B. D., van Wanrooij, M., Munoz, D. P., & van Opstal, A. J. (2002). Auditory-visual interactions subserving goal-directed saccades in a complex scene. *Journal of Neurophysiology*, **88**, 438-454.

Davis, K. A. (2005). Spectral processing in the inferior colliculus. *International Review of Neurobiology*, **70**, 169-205.

Davis, K. A., Ramachandran, R., & May, B. J. (2003). Auditory processing of spectral cues for sound localization in the inferior colliculus. *Journal of the Association for Research in Otolaryngology*, **4**, 148-163.

Diederich, A., & Colonius, H. (2008). Crossmodal interaction in saccadic reaction time: Separating multisensory from warning effects in the time window of integration model. *Experimental Brain Research*, **186**, 1-22.

Driver, J., & Spence, C. [J.] (1994). Spatial synergies between auditory and visual attention. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconcious information processing* (pp. 311-331). Cambridge, MA: MIT Press.

Electric cars must make noise under new EU rules. (2014, April 2nd). Retrieved May 26, 2017, from http://www.bbc.co.uk/news/world-europe-26857743.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, **415**, 429-433.

Farnè, A., & Làdavas, E. (2002). Auditory peripersonal space in humans. *Journal of Cognitive Neuroscience,* **14**, 1030-1043.

Ferris, T. K., & Sarter, N. B. (2008). Cross-modal links among vision, audition, and touch in complex environments. *Human Factors,* **50**, 17-26.

Finocchietti, S., Cappagli, G., Baud-Bovy, G., Magnusson, C., Caltenco, H., Wilson, G., et al. (2015). ABBI, a new technology for sensory-motor rehabilitation of visual impaired people. In *International Conference on Enabling Access for Persons with Visual Impairment* (pp. 80-84).

Finocchietti, S., Cappagli, G., & Gori, M. (2017). Auditory spatial recalibration in congenital blind individuals. *Frontiers in Neuroscience,* **11**:76.

Fitch, G. M., Kiefer, R. J., Hankey, J. M., & Kleiner, B. M. (2007). Toward developing an approach for alerting drivers to the direction of a crash threat. *Human Factors,* **49**, 710-720.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, **18**, 1030-1044.

Frissen, I., Vroomen, J., de Gelder, B., & Bertelson, P. (2003). The aftereffects of ventriloquism: Are they sound-frequency specific? *Acta Psychologica*, **113**, 315-327.

Frissen, I., Vroomen, J., de Gelder, B., & Bertelson, P. (2005). The aftereffects of ventriloquism: Generalization across sound-frequencies *Acta Psychologica*, **118**, 93-100.

Furukawa, S., & Middlebrooks, J. C. (2002). Cortical representation of auditory space: Information-bearing features of spike patterns. *Journal of Neurophysiology,* **87**, 1749-1762.

Gaver, W. W. (1986). Auditory icons: Using sound in computer interfaces. *Human-Computer Interaction,* **2**, 167-177.

Gaver, W. W. (1993a). What in the world we hear? An ecological approach to auditory event perception. *Ecological Psychology,* **5**, 1-29.

Gaver, W. W. (1993b). How do we hear in the world? Explorations in ecological acoustics. *Ecological Psychology,* **5**, 285-313.

Gori, M., Vercillo, T., Sandini, G., & Burr, D. (2014). Tactile feedback improves auditory spatial localization. *Frontiers in Psychology,* **5**:1121.

Graziano, M. S. A., Gross, C. G., Taylor, C. S. R., & Moore, T. (2004). A system of multimodal areas in the primate brain. In C. Spence & J. Driver (Eds.), *Crossmodal space and crossmodal attention* (pp. 51-67). Oxford, UK: Oxford University Press.

Graziano, M. S. A., Reiss, L. A. J., & Gross, C. G. (1999). A neuronal representation of the location of nearby sounds. *Nature,* **297**, 428-430.

Grothe, B., Pecka, M., & McAlpine, D. (2010). Mechanisms of sound localization in mammals. *Physiological Reviews,* **90**, 983-1012.

Grusser, O.-J. (1983). Multimodal structure of the extrapersonal space. In A. Hein & M. Jeannerod (Eds.), *Spatially oriented behavior* (pp. 327-352). New York, NY: Springer-Verlag.

Hancock, P. A., Mercado, J. E., Merlo, J., & Van Erp, J. B F. (2013). Improving target detection in visual search through the augmenting multi-sensory cues. *Ergonomics,* **56**, 729-738.

Hartmann, W. M., & Rakerd, B. (1993). Auditory spectral discrimination and the localization of clicks in the sagittal plane. *Journal of the Acoustical Society of America*, **94**, 2083-2092.

Hebrank, J., & Wright, D. (1974). Spectral cues used in the localization of sound sources on the median plane. *Journal of the Acoustical Society of America*, **56**, 1829-1834.

Heffner, H. E., & Heffner, R. S. (1990). Effect of bilateral auditory cortex lesions on sound localization in Japanese macaques. *Journal of Neurophysiology*, **64**, 915-931.

Heffner, R. S., & Heffner, H. E. (1992a). Evolution of sound localization in mammals. In D. B. Webster, R. R. Fay, & A. N. Popper (Eds.), *The evolutionary biology of hearing* (pp. 691-715). New York, NY: Springer-Verlag.

Heffner, R. S., & Heffner, H. E. (1992b). Visual factors in sound localization in mammals. *Journal of Comparative Neurology*, **317**, 219-232.

Heffner, H. E., & Masterton, R. B. (1975). The contributions of auditory cortex to sound localization in the monkey. *Journal of Neurophysiology*, **38**, 1340-1358.

Helbig, H. B., and Ernst, M. O. (2007). Knowledge about a common source can promote visual-haptic integration. Perception, **36**, 1523-1533.

Ho, C., & Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of Experimental Psychology: Applied*, **11**, 157-174.

Ho, C., & Spence, C. (2008). *The multisensory driver: Implications for ergonomic car interface design*. Aldershot, HA: Ashgate.

Ho, C., & Spence, C. (2009). Using peripersonal warning signals to orient a driver's gaze. *Human Factors*, **51**, 539-556.

Ho, C., Spence, C., & Tan, H. Z. (2005). Warning signals go multisensory. *Proceedings of HCI International* 2005, **9**, Paper No. 2284, 1-10.

Ho, C., Tan, H. Z., & Spence, C. (2006). The differential effect of vibrotactile and auditory cues on visual spatial attention. *Ergonomics*, **49**, 724-738.

Hofman, P. M., & Van Opstal, A. J. (1998). Spectro-temporal factors in two-dimensional human sound localization. *Journal of the Acoustical Society of America*, **103**, 2634-2648.

Hofman, P. M., Van Riswick, J. G., & Van Opstal, A. J. (1998). Relearning sound localization with new ears. *Nature Neuroscience*, **1**, 417-421.

Ignashchenkova, A., Dicke, P. W., Haarmeier, T., & Their, P. (2004). Neuron-specific contribution of the superior colliculus to overt and covert shifts of attention. *Nature Neuroscience*, **7**, 56-64.

Jackson, C. V. (1953). Visual factors in auditory localization. *Quarterly Journal of Experimental Psychology*, **5**, 52-65.

Kadunce, D. C., Vaughan, W. J., Wallace, M. T., Benedek, G., & Stein, B. E. (1997). Mechanisms of within- and cross-modality suppression in the superior colliculus. *Journal of Neurophysiology*, **78**, 2834-2847.

Kadunce, D. C., Vaughan, W. J., Wallace, M. T., & Stein, B. E. (2001). The influence of visual and auditory receptive field organization on multisensory integration in the superior colliculus. *Experimental Brain Research*, **139**, 303-310.

King, A. (2004). Development of multisensory spatial integration. In C. Spence & J. Driver (Eds.), *Crossmodal space and crossmodal attention* (pp. 1-24). Oxford, UK: Oxford University Press.

King, A. J. (2009). Visual influences on auditory spatial learning. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **364**, 331-339.

Kitagawa, N., Zampini, M., & Spence, C. (2005). Audiotactile interactions in near and far space. *Experimental Brain Research*, **166**, 528-537.

Klein, R. (2000). Inhibition of return. *Trends in Cognitive Sciences,* **4**, 138-147.

Knudsen, E. I. (2002). Instructed learning in the auditory localization pathway of the barn owl. *Nature*, **417**, 322-328.

Kóbor, I., Füredi, L., Kovács, G., Spence, C., & Vidnyánszky, Z. (2006). Back-to-front: Improved tactile discrimination performance in the space you can't see. *Neuroscience Letters*, **400**, 163-167.

Krech, D., & Crutchfield, R. S. (1958). *Elements of psychology*. New York, NY: A. A. Knopf.

Kustov, A. A., & Robinson, D. L. (1996). Shared neural control of attentional shifts and eye movements. *Nature*, **384**, 74-77.

Langendijk, E. H. A., & Bronkhorst, A. W. (2002). Contribution of spectral cues to human sound localization. *Journal of the Acoustical Society of America*, **112**, 1583-1596.

Laumen, G., Ferber, A. T., Klump, G. M., & Tollin, D. J. (2016). The physiological basis and clinical use of the binaural interaction component of the auditory brainstem response**.** *Ear & Hearing*, **37**, e276-e290.

Lee, C. C., & Middlebrooks, J. C. (2011). Auditory cortex spatial sensitivity sharpens during task performance. *Nature Neuroscience*, **14**, 108-114.

Lee, C. C., & Middlebrooks, J. C. (2013). Specialization for sound localization in fields A1, DZ, and PAF of cat auditory cortex. *Journal of the Association for Research Otolaryngology*, **14**, 61-82.

Lee, J., & Spence, C. (2015). Audiovisual crossmodal cuing effects in front and rear space. *Frontiers in Psychology*, **6**:1-10.

Lee, J., & Spence, C. (2017). On the spatial specificity of audiovisual crossmodal exogenous cuing effects. *Acta Psychologica*, **177**, 78-88.

Lee, S., Olsen, E., & Wierwille, W. (2004). A comprehensive examination of naturalistic lane-changes. *U.S. Department of Transportation, DOT HS 809 702.*

Leo, F., Bertini, C., di Pellegrino, G., & Ladavas, E. (2008). Multisensory integration for orienting responses in humans requires the activation of the superior colliculus. *Experimental Brain Research*, **186**, 67-77.

Lomber, S. G., Malhorta, S., & Hall, A. J. (2007). Functional specialization in non-primary auditory cortex of the cat: Areal and laminar contributions to sound localization. *Hearing Research*, **222**, 31-45.

Los, S. A., & Schut, M. L. (2008). The effective time course of preparation. *Cognitive Psychology*, **57**, 20-55.

Los, S. A., & Van der Burg, E. (2013). Sound speeds vision through preparation, not integration. *Journal of Experimental Psychology: Human Perception and Performance*, **39**, 1612-1624.

Lovejoy, L. P., & Krauzlis, R. J. (2010). Inactivation of primate superior colliculus impairs covert selection of signals for perceptual judgments. *Nature Neuroscience,* **13**, 261-267.

Macpherson, E. A., & Middlebrooks, J. C. (2000). Localization of brief sounds: Effects of level and background noise. *Journal of the Acoustical Society of America*, **108**, 1834-1849.

Makous, J. C., & Middlebrooks, J. C. (1990). Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America*, **87**, 2188-2200.

Malhorta, S., Hall, A. J., & Lomber, S. G. (2004). Cortical control of sound localization in the cat: Unilateral cooling deactivation of 19 cerebral areas. *Journal of Neurophysiology*, **92**, 1625-1643.

Malhorta, S., Stecker, G. C., Middlebrooks, J. C., & Lomber, S. G. (2008). Sound localization deficits during reversible deactivation of primary auditory cortex and/or the dorsal zone. *Journal of Neurophysiology*, **99**, 1628-1642.

Maravita, A., Spence, C., Sergent, C., & Driver, J. (2002). Seeing your own touched hands in a mirror modulates cross-modal interactions. *Psychological Science,* **13**, 350-356.

McDonald, J. J., Teder-Sälejärvi, W. A., & Ward, L. M. (2001). Multisensory integration and crossmodal attention effects in the human brain. *Science*, **292**, 1791-1791.

McDonald, J. J., & Ward, L. M. (1999). Spatial relevance determines facilitatory and inhibitory effects of auditory covert spatial orienting. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 1234-1252.

McIntire, J. P., Havig, P. R., Watamaniuk, S. N., & Gilkey, R. H. (2010). Visual search performance with 3-D auditory cues: Effects of motion, target location, and practice. *Human Factors*, **52**, 41-53.

McKeown, D., & Isherwood, S. (2007). Mapping candidate within-vehicle auditory displays to their referents. *Human Factors*, **49**, 417-428.

Mehrgardt, S., & Mellert, V. (1977). Transformation characteristics of the external human ear. *Journal of the Acoustical Society of America*, **61**, 1567-1576.

Mendonça, C. (2014). A review on auditory space adaptations to altered head-related cues. *Frontiers in Neuroscience*, **8**:219.

Meredith, M. A., & Stein, B. E. (1996). Spatial determinants of multisensory integration in cat superior colliculus neurons. *Journal of Neurophysiology,* **75**, 1843-1857.

Mickey, B. J., & Middlebrooks, J. C. (2003). Representation of auditory space by cortical neurons in awake cats. *Journal of Neuroscience*, **23**, 8649-8663.

Middlebrooks, J. C. (2014). Distributed cortical representation of sound locations. In A. N. Popper & R. R. Fay (Eds.), *Perspectives on auditory research* (pp. 361-378). New York, NY: Springer Science+Business Media.

Middlebrooks, J. C., Clock, A. E., Xu, L., & Green, D. M. (1994). A panoramic code for sound location by cortical neurons. *Science,* **264**, 842-844.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology,* **42,** 135-159.

Middlebrooks, J. C., & Knudsen, E. I. (1984). A neural code for auditory space in the cat's superior colliculus. *Journal of Neuroscience*, **4**, 2621-2634.

Middlebrooks, J. C., Xu, L., Eddins, A. C., & Green, D. M. (1998). Codes for soundsource location in nontonotopic auditory cortex. *Journal of Neurophysiology*, **80**, 863-881.

Moeller, B., Zoppke, H., & Frings, C. (2016). What a car does to your perception: Distance evaluations differ from within and outside of a car. *Psychonomic Bulletin & Review*, **23**, 781-788.

Mondor, T. A., & Zatorre, R. J. (1995). Shifting and focusing auditory spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, **21**, 387-409.

Moore, T., Armstrong, K. M., & Fallah, M. (2003). Visuomotor origins of covert spatial attention. *Neuron*, **40**, 671-683.

Mrsic-Flogel, T. D., King, A. J., & Schnupp, J. W. H. (2005). Encoding of virtual acoustic space stimuli by neurons in ferret primary auditory cortex. *Journal of Neurophysiology*, **93**, 3489-3503.

Münte, T. F., Kohlmetz, C., Nager, W., & Altenmüller, E. (2001). Superior auditory spatial tuning in conductors. *Nature*, **409**, 580.

Musicant, A. D., & Butler, R. A. (1984). The influence of pinnae-based spectral cues on sound localization. *Journal of the Acoustical Society of America*, **75**, 1195-1200.

Musicant, A. D., Chan, J. C., & Hind, J. E. (1990). Direction-dependent spectral properties of cat external ear: New data and cross-species comparisons. *Journal of the Acoustical Society of America*, **87**, 757-781.

Nakamoto, K. T., Jones, S. J., & Palmer, A. R. (2008). Descending projections from auditory cortex modulate sensitivity in the midbrain to cues for spatial position. *Journal of Neurophysiology*, **99**, 2347-2356.

Occelli, V., O'Brien, J. H., Spence, C., & Zampini, M. (2010). Assessing the audiotactile Colavita effect in near and rear space. *Experimental Brain Research*, **203**, 517-532.

Occelli, V., Spence, C., & Zampini, M. (2011). Audiotactile interactions in front and rear space. *Neuroscience & Biobehavioral Reviews*, **35,** 589-598.

Ortiz-Rios, M., Azevedo, F. A. C., Kuśmierek, P., Balla, D. Z., Munk, M. H., Keliris, G. A., et al. (2017). Location in macaque auditory cortex. *Neuron*, **93**, 971-983.

Ovcharenko, A., Cho, S. J., & Chong, U. P. (2007). Front-back confusion resolution in three-dimensional sound localization using databases built with a dummy head. *Journal of the Acoustical Society of America*, **122**, 489-495.

Parise, C. V., Harrar, V., Ernst, M. O., & Spence, C. (2013). Cross-correlation between auditory and visual signals promotes multisensory integration. *Multisensory Research*, **26**, 307-316.

Parise, C. V., Knorre, K., & Ernst, M. O. (2014). Natural auditory scene statistics shapes human spatial hearing. *Proceedings of the National Academy of Sciences of the USA*, **111**, 6104-6108.

Parise, C. V., Spence, C., & Ernst, M. (2012). When correlation implies causation in multisensory integration. *Current Biology*, **22**, 46-49.

Pavani, F., & Castiello, U. (2004). Binding personal and extrapersonal space through body shadows. *Nature Neuroscience*, **7**, 13-14.

Pavani, F., & Galfano, G. (2007). Self-attributed body-shadows modulate tactile attention. *Cognition*, **104**, 73-88.

Perrett, S., & Noble, W. (1997). The contribution of head motion cues to localization of low-pass noise. *Attention, Perception, & Psychophysics*, **59**, 1018-1026.

Perrott, D. R. (1993). Auditory and visual localization: Two modalities and one world. *Proceedings of the Audio Engineering Society 12th International Conference.* Snekkersten, Copenhagen (pp. 221-231).

Perrott, D. R., Cisneros, J., McKinley, R. L., & D'Angelo, W. R. (1996). Aurally aided visual search under virtual and free-field listening conditions. *Human Factors*, **38**, 702-715.

Perrott, D. R., & Saberi, K. (1990). Minimum audible angle thresholds varying in both elevation and azimuth. *Journal of the Acoustic Society of America*, **87**, 1728-1731.

Perrott, D. R., Saberi, K., Brown, K., & Strybel, T. Z. (1990). Auditory psychomotor coordination and visual search performance. *Perception & Psychophysics*, **48**, 214-226.

Perrott, D. R., Sadralodabai, T., Saberi, K., & Strybel, T. Z. (1991). Aurally aided visual search in the central visual field: Effects of visual load and visual enhancement of the target. *Human Factors*, **33**, 389-400.

Petiot, J.-F., Kristensen, B. G., & Maier, A. M. (2013). How should an electric vehicle sound? User and expert perception. *Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2013*. August 4-7, 2013, Portland, Oregon, USA.

Populin, L. C., & Yin, T. C. T. (1998). Sensitivity of auditory cells in the superior colliculus to eye position in the behaving cat. In A. R. Palmer, A. Rees, A. Q., Summerfield, & R. Meddis (Eds.), *Psychophyscial and physiological advances in hearing* (pp. 441-448). London, UK: Whurr.

Populin, L. C., & Yin, T. C. T. (2002). Bimodal interactions in the superior colliculus of the behaving cat. *Journal of Neuroscience*, **22**, 2826-2834.

Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin*, **124**, 123-164.

Previc, F. H. (2000). Neuropsychological guidelines for aircraft control stations. *IEEE Engineering in Medicine and Biology Magazine*, **19**, 81-88.

Rayleigh, L. (1907). XII. On our perception of sound direction. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, **13(74)**, 214-232.

Reale, R. A., Brugge, J. F., & Hind, J. E. (2000). Directional sensitivity of neurons in the primary auditory (AI) cortex of the cat to successive sounds ordered in time and space. *Journal of Neurophysiology*, **84**, 435-450.

Reale, R. A., Jension, R. L., & Brugge, J. F. (2003). Directional sensitivity of neurons in the primary auditory (AI) cortex: Effects of sound-source intensity level. *Journal of Neurophysiology*, **89**, 1024-1038.

Recanzone, G. H. (1998). Rapidly induced auditory plasticity: The ventriloquism aftereffect. *Proceedings of the National Academy of Sciences of the USA*, **95**, 869-875.

Röder, B., Teder-Saläjärvi, W., Sterr, A., Rösler, F., Hillyard, S. A., & Neville, H. J. (1999). Improved auditory spatial tuning in blind humans. *Nature*, **400**, 162-166.

Rudmann, D. S., & Strybel, T. Z. (1999). Auditory spatial facilitation of visual search performance: Effect of cue precision and distractor density. *Human Factors*, **41**, 146-160.

Sambo, C. F., & Forster, B. (2011). When far is near: ERP correlates of crossmodal spatial interactions between tactile and mirror-reflected visual stimuli. *Neuroscience Letters*, **500**, 10-15.

Scharf, B. (1998). Auditory attention: The psychoacoustical approach. In H. Pashler (Ed.), *Attention* (pp. 75-117). London, UK: Psychology Press.

Schnupp, J. W. H., Mrsic-Flogel, T. D., & King, A. J. (2001). Linear processing of spatial cues in primary auditory cortex. *Nature*, **414**, 200-204.

Schnupp, J., Nelken, I., & King, A. (2011). *Auditory neuroscience: Making sense of sound*. Cambridge, MA: MIT Press.

Schreiner, C. E., Froemke, R. C., & Atencio, C. A. (2011). Spectral processing in auditory cortex. In J. A. Winer & C. E. Schreiner (Eds.), *The auditory cortex* (pp. 275-308). New York, NY: Springer.

Shilling, R. D., & Shinn-Cunningham, B. (2000). Virtual auditory displays. In K. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications* (pp. 65-92). Mahwah, NJ: Lawrence Erlbaum.

Shinn-Cunningham, B. G., Santarelli, S., & Kopco, N. (2000). Tori of confusion: Binaural localization cues for sources within reach of a listener. *Journal of the Acoustical Society of America*, **107**, 1627-1636.

Slattery, W. H., & Middlebrooks, J. C. (1994). Monaural sound localization: Acute versus chronic unilateral impairment. *Hearing Research*, **75**, 38-46.

Slutsky, D. A., & Recanzone, G. H. (2001). Temporal and spatial dependency of the ventriloquism effect. *Neuroreport*, **12**, 7-10.

Spence, C. (2001). Crossmodal attentional capture: A controversy resolved? In C. Folk & B. Gibson (Eds.), *Attention, distraction and action: Multiple perspectives on attentional capture* (pp. 231-262). Amsterdam: Elsevier Science BV.

Spence, C. (2010). Crossmodal spatial attention. *Annals of the New York Academy of Sciences (The Year in Cognitive Neuroscience)*, **1191**, 182-200.

Spence, C. (2012). Drive safely with neuroergonomics. *The Psychologist*, **25**, 664-667.

Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, **1296,** 31-49.

Spence, C. (2014). Orienting attention: A crossmodal perspective. In A. C. Nobre & S. Kastner (Eds.), *The Oxford handbook of attention* (pp. 446-471). Oxford, UK: Oxford University Press.

Spence, C. (J.), & Driver, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 555-574.

Spence, C., & Driver, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics*, **59**, 1-22.

Spence, C., & Driver, J. (2000). Attracting attention to the illusory location of a sound: Reflexive crossmodal orienting and ventriloquism. *NeuroReport*, **11**, 2057-2061.

Spence, C., & Driver, J. (Eds.). (2004). *Crossmodal space and crossmodal attention*. Oxford, UK: Oxford University Press.

Spence, C., & Ho, C. (2015). Crossmodal attention: From the laboratory to the real world (and back again). In J. M. Fawcett, E. F. Risko, & A. Kingstone (Eds.), *The handbook of attention* (pp. 119-138). Cambridge, MA: MIT Press.

Spence, C., Lloyd, D., McGlone, F., Nicholls, M. E. R., & Driver, J. (2000). Inhibition of return is supramodal: A demonstration between all possible pairings of vision, touch and audition. *Experimental Brain Research*, **134**, 42-48.

Spence, C., & McDonald, J. (2004). The cross-modal consequences of the exogenous spatial orienting of attention. In G. A. Calvert, C. Spence, & B. E. Stein (Eds.), *The handbook of multisensory processes* (pp. 3–26). Cambridge, MA: MIT Press.

Spence, C., Nicholls, M. E. R., Gillespie, N., & Driver, J. (1998). Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision. *Perception & Psychophysics*, **60**, 544-557.

Spence, C., Parise, C., & Chen, Y.-C. (2011). The Colavita visual dominance effect. In M. M. Murray & M. Wallace (Eds.), *Frontiers in the neural bases of multisensory processes* (pp. 523-550). Boca Raton, FL: CRC Press.

Spence, C., Ranson, J., & Driver, J. (2000). Crossmodal selective attention: Ignoring auditory stimuli presented at the focus of visual attention. *Perception & Psychophysics*, **62**, 410-424.

Spence, C., & Read, L. (2003). Speech shadowing while driving on the difficulty of splitting attention between eye and ear. *Psychological Science*, **14**, 251-256.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses.* Cambridge, MA: MIT Press.

Strelnikov, K., Rosito, M., & Barone, P. (2011). Effect of audiovisual training on monaural spatial hearing in horizontal plane. *PLoS ONE*, **6(3)**:e18344.

Talagala, D. S., Zhang, W., Abhayapala, T. D., & Kamineni, A. (2014). Binaural sound source localization using the frequency diversity of the head-related transfer function. *Journal of the Acoustical Society of America*, **135**, 1207-1217.

Thompson, G. C., & Masterton, R. B. (1978). Brain stem auditory pathways involved in reflexive head orientation to sound. *Journal of Neurophysiology*, **41**, 1183-1202.

Tipper, S. P., Lloyd, D., Shorland, B., Dancer, C., Howard, L. A., & McGlone, F. (1998). Vision influences tactile perception without proprioceptive orienting. *Neuroreport*, **9**, 1741-1744.

Tipper, S. P., Phillips, N., Dancer, C., Lloyd, D., Howard, L. A., & McGlone, F. (2001). Vision influences tactile perception at body sites that cannot be viewed directly. *Experimental Brain Research*, **139**, 160-167.

Van der Stoep, N., Nijboer, T. C., & Van der Stigchel, S. (2014). Exogenous orienting of crossmodal attention in 3-D space: Support for a depth-aware crossmodal attentional system. *Psychonomic Bulletin & Review*, **21**, 708-714.

Van der Stoep, N., Nijboer, T. C. W., Van der Stigchel, S., & Spence, C. (2015a). Multisensory interactions in the depth plane in front and rear space: A review. *Neuropsychologia*, **70**, 335-349.

Van der Stoep, N., Serino, A., Farnè, A., Di Luca, M., & Spence, C. (2016a). Depth: The forgotten dimension in multisensory research. *Multisensory Research*, **29**, 493-524.

Van der Stoep, N., Spence, C., Nijboer, T. C. W., & Van der Stigchel, S. (2015b). On the relative contributions of multisensory integration and crossmodal exogenous spatial attention to multisensory response enhancement. *Acta Psychologica*, **162**, 20-28.

Van der Stoep, N., Van der Stigchel, S., Nijboer, T. C. W., & Van der Smagt, M. J. (2016b). Audiovisual integration in near and far space: Effects of changes in distance and stimulus effectiveness. *Experimental Brain Research*, **234**, 1175-1188.

Van Wanrooij, M. M., & Van Opstal, A. J. (2005). Relearning sound localization with a new ear. *Journal of Neuroscience*, **25**, 5413-5424.

Vroomen, J., Bertelson, P., & de Gelder, B. (2001). Directing spatial attention towards the illusory location of a ventriloquized sound. *Acta Psychologica*, **108**, 21-33.

Vu, K. P. L., Strybel, T. Z., & Proctor, R. W. (2006). Effects of displacement magnitude and direction of auditory cues on auditory spatial facilitation of visual search. *Human Factors*, **48**, 587-599.

Wagner, H. (1993). Sound-localization deficits induced by lesions in the barn owl's auditory space map. *Journal of Neuroscience*, **13**, 371-386.

Wallace, M. T., Roberson, G. E., Hairston, W. D., Stein, B. E., Vaughan, J. W., & Schirillo, J. A. (2004). Unifying multisensory signals across time and space. *Experimental Brain Research*, **158**, 252-258.

Wallace, M. T., Wilkinson, L. K., & Stein, B. E. (1996). Representation and integration of multiple sensory inputs in primate superior colliculus. *Journal of Neurophysiology*, **76**, 1246-1266.

Wallach, H. (1940). The role of head movements and vestibular and visual cues in sound localization. *Journal of Experimental Psychology*, **27**, 339-368.

Wenzel, E. M. (1992). Localization in virtual acoustic displays. *Presence: Teleoperators & Virtual Environments*, **1**, 80-107.

Wenzel, E. M., Arruda, M., Kistler, D. J., & Wightman, F. L. (1993). Localization using nonindividualized head-related transfer functions. *Journal of the Acoustical Society of America*, **94**, 111-123.

Wightman, F. L., & Kistler, D. J. (1989). Headphone stimulation of free-fields listening. II: Psychophysical validation. *Journal of the Acoustical Society of America*, **85**, 868-878.

Wightman, F. L., & Kistler, D. J. (1997). Monaural sound localization revisited. *Journal of the Acoustical Society of America*, **101**, 1050-1063.

Wightman, F. L., & Kistler, D. J. (1999). Resolution of front–back ambiguity in spatial hearing by listener and source movement. *Journal of the Acoustical Society of America*, **105**, 2841-2853.

Yin, T. C. (2002). Neural mechanisms of encoding binaural localization cues in the auditory brainstem. In D. Oertel., R. R. Fay., & A. N. Popper (Eds.), *Integrative functions in the mammalian auditory pathway* (pp. 99-159). New York, NY: Springer.

Zaidel, A., Turner, A. H., & Angelaki, D. E. (2011). Multisensory calibration is independent of cue reliability. *Journal of Neuroscience*, **31**, 13949-13962.

Zaidel, A., Ma, W. J., & Angelaki, D. E. (2013). Supervised calibration relies on the multisensory percept. *Neuron*, **80**, 1544-1557.

Zampini, M., Torresan, D., Spence, C., & Murray, M. M. (2007). Audiotactile multisensory interactions in front and rear space. *Neuropsychologia*, **45**, 1869-1877.

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex*, **11**, 946-953.

Zhang, P. X., & Hartmann, W. M. (2010). On the ability of human listeners to distinguish between front and back. *Hearing Research*, **260**, 30-46.

Zwiers, M. P., Van Opstal, A. J., & Paige, G. D. (2003). Plasticity in human sound localization induced by compressed spatial vision. *Nature Neuroscience*, **6**, 175-181.