Auditory Cuing of Visual Attention:

Spatial and Sound Parameters



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A thesis submitted for the degree of

Doctor of Philosophy

Trinity 2017

Declaration

I hereby declare that this work has not been submitted previously as an exercise for a degree at this or any other university, and that it is entirely my own work.

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Publications resulting from this thesis

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.

Spence, C., Lee, J., & Van der Stoep, N. (in press). Responding to sounds from unseen locations: Crossmodal attentional orienting in response to sounds presented from the rear. *European Journal of Neuroscience*.

Lee, J., & Spence, C. (submitted). Assessing the influence of sound parameters on crossmodal cuing in different regions of space. *Acta Psychologica*.

Acknowledgements

I would like to express my deepest gratitude to Professor Charles Spence, my supervisor, for his patience and guidance throughout my DPhil. More importantly, he taught me logic. For that, I am eternally grateful.

I would also like to thank Dr. Mihaela Duta for helping me develop the programming skills I needed for my DPhil. Most of all, I am deeply grateful for her encouragement when I felt defeated.

Lastly, I would like to thank, although I do not know how, my loving parents, Professor Kang Yong Lee and Un Soo Chung. My achievement is a mere reflection of their unconditional support. This thesis is dedicated to my parents.

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List of abbreviation

AES – anterior ectosylvian sulcus

CMF – cortical magnification factor

ER – error rate

ERP – event-related brain potential

IC – inferior colliculus

ILD – interaural level difference

ITD – interaural time difference

IQR – interquartile range

ISI – interstimulus range

MTG – middle temporal gyrus

OPR – Oxford Psychology Research

RSV(A)P – rapid sequential visual (or auditory) presentation

RT – reaction time

RF – receptive field

RM-ANOVA – repeated measures analysis of variance

RPS – Research Participation Scheme

SE – standard error

SOA – stimulus onset asynchrony

SC – superior colliculus

STS – superior temporal sulcus

Abstract

The experiments reported in this thesis investigate whether the current understanding of crossmodal spatial attention can be applied to rear space, and how sound parameters can modulate crossmodal spatial cuing effects. It is generally accepted that the presentation of a brief auditory cue can exogenously orient spatial attention to the cued region of space so that reaction times (RTs) to visual targets presented there are faster than those presented elsewhere. Unlike the conventional belief in such crossmodal spatial cuing effects, RTs to visual targets were equally facilitated from the presentation of an auditory cue in the front or in the rear, as long as the stimuli were presented ipsilaterally. Moreover, when an auditory cue and a visual target were presented from one of two lateral positions on each side in front, the spatial co-location of the two stimuli did not always lead to the fastest target RTs. Although contrasting with the traditional view on the importance of cue-target spatial co-location in exogenous crossmodal cuing effects, such findings are consistent with the evidence concerning multisensory integration in the superior colliculus (SC). Further investigation revealed that the presentation of an auditory cue with an exponential intensity change might be able to exogenously orient crossmodal spatial attention narrowly to the cued region of space. Taken together, the findings reported in this thesis suggest that not only the location but also sound parameters (e.g., intensity change) of auditory cues can modulate the crossmodal exogenous orienting of spatial attention.

Extended abstract

Studies have repeatedly demonstrated that the presentation of a brief auditory (e.g., pure tone or broadband) cue can exogenously orient crossmodal spatial attention to the cued region of space, facilitating RTs to visual targets presented there rather than elsewhere (see Spence & Driver, 1997a; see also Spence & McDonald, 2004; Spence, McDonald, & Driver, 2004, for reviews). Such crossmodal spatial cuing effects are known to last only for approximately 300ms, particularly in detection studies, between the onset of a cue and that of a target (i.e., stimulus onset asynchrony [SOA]; see Klein, 2000; Spence et al., 2004; see also Spence, Nicholls, Gillespie, & Driver, 1998). The evidence in support of such crossmodal spatial cuing effects has been documented mostly from studies that have presented the cue and target stimuli either on the left or right side in front of the participant. Nonetheless, it is commonly believed that the presentation of a brief auditory cue, typically lasting for 100ms or less (e.g., McDonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Spence & Driver, 1997a), can exogenously orient spatial attention narrowly to the cued region of space rather than the entire hemifield (Driver & Spence, 1998; Ho & Spence, 2005; see also Spence & McDonald, 2004; Spence et al., 2004, for reviews). In other words, crossmodal cuing effects are generally thought to be spatially-specific. Given the reported crossmodal attentional link between the auditory and visual systems (see Spence & Driver, 2004, for a review), there has been a growing interest in implementing the insights from crossmodal spatial cuing effects in the design of in-vehicle warning signals (see Ho & Spence, 2008; Spence & Ho, 2015). Crossmodal spatial cuing effects have been confirmed in driving stimulation studies, and the research interest in the applied ergonomics has expanded to developing in-vehicle auditory

warning signals using ecologically meaningful sounds such as auditory cues with exponentially increasing intensity (i.e., looming cues; see Gray 2011; Ho, Spence, & Gray, 2013).

Despite the abundant evidence in support of the existence of crossmodal spatial cuing effects, it is still unclear how narrowly the presentation of an auditory cue can exogenously orient one's attention to the cued region of space. It is important to further examine the spatial specificity of audiovisual cuing effects (i.e., involving auditory cues and visual targets) before researchers can safely recommend using auditory stimuli to orient driver's attention to the direction of potential danger. After all, the visual field only extends to a maximum of roughly 90° to either side of the current line of gaze (see Perrott, 1993; Spector, 1990), and driving requires one to pay attention to the surrounding of his/her vehicle. Furthermore, it is unclear whether sound parameters such as cue intensity, cue duration, or waveform structure (e.g., pure tone, triangle waveform, broadband, etc.) can modulate the crossmodal exogenous orienting of spatial attention. Therefore, it is important to investigate whether, and how, sound parameters interact with crossmodal spatial cuing effects, before the designers of in-vehicle warning system implement, for instance, looming sounds to be used as warning signals. This thesis investigates whether the current understanding of crossmodal spatial cuing effects (i.e., spatial specificity) can be generalised to the space outside the frontal space and to the use of complex sound, such as looming auditory cues.

The experiments reported in Chapter 2 were designed to investigate the spatial specificity of crossmodal cuing effect and whether the presentation of a looming sound with a duration of 1,000ms would elicit a cuing effect (cf. Klein, 2000). Using brief white noise auditory cues, Experiment 1 tried and replicated the crossmodal spatial cuing effect reported in Spence and Driver (1997a), confirming that the apparatus set-up was

sensitive enough to detect cuing effects. Experiment 2 was conducted in order to investigate the spatial specificity of audiovisual cuing effect for frontal visual targets using brief white noise auditory cues randomly presented from one of four locations: front-left, front-right, rear-left, or rear-right. Given the reported spatial specificity of crossmodal cuing effects, it was hypothesised that the magnitude of a crossmodal spatial cuing effect following the presentation of an auditory cue in the frontal space would be larger than that in the rear (Driver & Spence, 1998; Spence et al., 2004). Surprisingly, however, the presentation of an auditory cue facilitated the perception of visual targets when the cue and target stimuli were presented ipsilaterally, regardless of whether the cues were presented from the front or rear. With the same apparatus set-up as in Experiment 2, Experiment 3 repeated the procedure of Experiment 2 using a looming white noise auditory cue or a constant-intensity white noise cue (both for a duration of 1,000ms). The hypothesis was that the presentation of an auditory cue, no matter whether it was a looming or a constant-intensity cue, would not elicit any spatial cuing effect. However, the results of Experiment 3 revealed a significant crossmodal spatial cuing effect following the presentation of a looming auditory cue. What is more, the cuing effect from looming auditory cues was larger when the cues were presented from the front than from the rear. In other words, the crossmodal cuing effect was spatially-specific following the presentation of a looming auditory cue.

The experiments reported in Chapter 3 were designed to further investigate the findings of Experiment 2 with a different apparatus set-up compared to that in Chapter 2. Experiment 4 was conducted in order to replicate the crossmodal spatial cuing effect reported in Experiment 1 and Spence and Driver's (1997a) study, using simple (pure tone vs. white noise) auditory and visual stimuli presented from the frontal space only. Following the replication of the crossmodal spatial cuing effect in Experiment 4, an

additional pair of loudspeakers was added to the space behind the participant's head for Experiment 5. The data from Experiment 5 revealed the same results as in Experiment 2; the magnitude of a crossmodal spatial cuing effect was the same regardless of whether the auditory cues were presented from the front or rear. The sound waveform (pure tone vs. white noise) did not modulate crossmodal spatial cuing effects in Experiments 4 and 5. Experiment 6 was conducted in order to investigate whether the participants would experience any front-back confusion in a sound location discrimination task in which the auditory cues used in Experiment 5 now became auditory targets. The findings suggested that the participants did not confuse the front-back location of auditory targets. Although controversial to the general belief on the spatial specificity of crossmodal cuing effects, the findings reported in Experiments 2 and 5 are, however, consistent with the literature on the response properties of multisensory neurons in the SC (see Stein & Meredith, 1993, for a review).

The results from Experiments 2 and 5 suggest that the exact co-location of the auditory cue and the visual target is not always critical to elicit a significant crossmodal spatial cuing effect, at least not when the cues are presented from the rear. In order to confirm the spatial specificity of crossmodal cuing effects in frontal space, the experiments reported in Chapter 4 were designed to replicate the findings reported in Driver and Spence (1998) using brief white noise auditory cues. Four loudspeakers (two on each side) for presenting auditory cues were placed horizontally in front of participants, with two visual target LEDs installed directly below and above each loudspeaker. Three experiments were conducted with different visual angles to the cue and/or target stimuli in each experiment, but the results were the same. RTs to visual targets were faster when the cue and target were presented from the same position than from different positions within the cued hemifield. However, this was only true when the cues were presented

from the inner eccentricity. Importantly, RTs to the inner eccentricity targets were faster than those to the outer targets, thus confirming the existence of eccentricity effect (Carrasco, Evert, Chang, & Katz, 1995). The lack of spatially-specific cuing effects within a hemifield following the cues presented from the outer eccentricity was therefore interpreted in terms of the eccentricity of visual targets interacting with crossmodal spatial cuing effects. Although the findings provide evidence against the spatial specificity of crossmodal cuing effects in front space (Driver & Spence, 1998), such findings are in line with the literature concerning the properties of multisensory neurons in the SC.

Based on the findings reported in Chapters 2-4, it became clear that crossmodal cuing effects were not as spatially-specific as some researchers have claimed, at least when traditional auditory (e.g., brief pure/white noise) cues were used. However, the conventional view concerning the spatial specificity of crossmodal cuing effects was confirmed when the looming white noise auditory cues (with a duration of 1,000ms) were used in Experiment 3 (Chapter 2). Such findings suggest that looming sounds could be more effective in exogenously orienting crossmodal spatial attention than brief auditory cues that have been traditionally used. Experiment 10 in Chapter 5 was designed to investigate how sound parameters such as cue duration (250 vs. 500ms), cue intensity (looming vs. receding), and waveform structure (triangle waveform [i.e., structured] vs. white noise) would modulate crossmodal spatial cuing effects, using a similar set-up as in Experiment 5.

The results of Experiment 10 revealed that the magnitude of a crossmodal spatial cuing effect was larger following the presentation of a looming auditory cue in front than from the rear, regardless of the cue durations and the waveform structures. What is more, the crossmodal spatial cuing effect following the presentation of a structured auditory cue

was larger in the looming cue condition than in the receding cue condition. There was no such perceptual bias towards looming sounds in preference to receding sounds in the white noise cue condition. In order to investigate whether such findings were attributable to the extended SOAs, Experiment 11 was conducted to try and replicate the findings of Experiments 2 and 5 using brief white noise burst cues, with the SOAs of 100, 250, or 500ms. The data from Experiment 11 replicated the findings reported in Experiments 2 and 5; the magnitude of a crossmodal spatial cuing effect was not statistically different no matter whether the cues were presented from the front or rear. Therefore, the spatially-specific cuing effect and the perceptual bias towards looming sounds in preference to receding sounds documented in Experiment 10 were attributable to the sound parameters such as the cue intensity change and the waveform structure. Taken together, the findings reported in this thesis therefore suggest that exogenous crossmodal spatial cuing effects can be modulated not only by the location of a presented auditory cue, but also by the sound parameters of the cue.

In the final chapter, potential limitations in the study design in each chapter are discussed, and how they were improved in the following chapter where applicable. I further discuss how the auditory cortex and the inferior colliculus (IC), along with the SC, could have contributed to the findings of Chapter 5 regarding the sound parameters modulating crossmodal spatial cuing effects. The thesis concludes with a suggestion that future studies involving auditory spatial cuing should broaden their horizons and consider the perception of (and response to) stimuli in rear space and of various sound parameters.

Chapter 1. Introduction

1.1. Brief overview of crossmodal spatial cuing effects

Over the last two or three decades, researchers have repeatedly demonstrated that the presentation of a task-irrelevant, spatially non-predictive auditory cue (typically lasting for 100ms or less; e.g., McDonald et al., 2003; Spence & Driver, 1997a) can facilitate RTs to subsequently presented visual targets on the cued side as compared to those on the uncued side (in this thesis, this will be referred to as the between-hemifield spatial cuing effect; e.g., Spence & Driver, 1997a; see Spence & Driver, 2004, for a review). Such exogenous spatial cuing effects are known to last only briefly (for up to 300ms in simple detection tasks; Fuentes & Campoy, 2008; Klein, 2000; Spence et al., 2004). It has also been reported that the presentation of an auditory cue can exogenously orient crossmodal spatial attention narrowly within the cued hemifield (in this thesis, this will be referred to as the within-hemifield spatial cuing effect; Driver & Spence, 1998; see also Schmitt, Postma, & de Haan, 2001). Based on the robust crossmodal attentional link documented between the auditory and visual systems, there has been a growing interest in applying the insights from crossmodal spatial cuing effects to the design of in-vehicle auditory warning signals (see Ho & Spence, 2008; Spence & Ho, 2015, for reviews) in order to compensate for driver inattention.[1] The findings from driving simulation studies

[1] According to the literature, driver inattention is defined as the failure to select relevant information (or any information; Victor, Engström, & Harbluk, 2008), or the delay in directing attention to the relevant information (Treat, 1980). It has often been blamed to be one of the leading causes for vehicle collisions (Beanland, Fitzharris, Young, & Lenné, 2013; Ho & Spence, 2008; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; Olson, Hanowski, Hickman, & Bocanegra, 2009). Therefore, the primary goal of in-vehicle auditory warning signals should be helping drivers to quickly perceive the relevant information, such as potential collision situations, to help enhance safe driving.

published to date have revealed that the presentation of an auditory cue either in the frontal or rear space could facilitate the perception of visual targets presented at the cued position (Ho & Spence, 2005; Ho, Tan, & Spence, 2006). Taken together, the evidence in support of the existence of exogenous crossmodal spatial cuing effects suggests that such cuing effects are spatially-specific; RTs to visual targets are fastest when the cue and target are presented from the same location (see Spence & McDonald, 2004; Spence et al., 2004; for reviews).

1.2. Crossmodal spatial cuing effects - spatial attention or multisensory integration?

There are two different perspectives (i.e., covert exogenous attention & multisensory integration) to explain the crossmodal exogenous orienting of spatial attention (see Spence et al., 2004). According to the attentional account, the presentation of a task-irrelevant auditory cue exogenously orients covert spatial attention to the perceived cued location. A target in another modality presented there can then be processed quickly due to the narrow focus of attention in that region of space. From the perspective of multisensory integration, a crossmodal spatial cuing effect is not the result of attentional facilitation at all; it is the result of the fusion between the information from two modalities (see Spence et al., 2004, for a discussion on the difference between multisensory integration and crossmodal attention). The distinction between multisensory integration and crossmodal attention is not clear, even today, as some commentators have argued that multisensory integration occurs mostly with stimuli presented simultaneously (see Spence et al., 2004, for a review; see also Chen & Spence, 2017). On the other hand, Macaluso, Frith, and Driver (2001) have argued that the distinction between multisensory integration and crossmodal attention is merely a

terminological issue. As 'multisensory integration' can occur with a temporal distance of up to 600ms (Meredith, Nemitz, & Stein, 1987; see also Van der Stoep, Spence, Nijboer, & Van der Stigchel, 2015a), this thesis will also refer to the neurophysiological data in multisensory integration when discussing crossmodal spatial attention.

The mechanisms of multisensory integration have been investigated mostly based on the response properties of multisensory neurons in the SC (see Stein & Meredith, 1993; Stein & Stanford, 2008, for reviews). The SC is a midbrain structure containing multiple layers, which are often divided into the superficial and deeper layers (e.g., Wallace, Wilkinson, & Stein, 1996). This midbrain structure is known to be involved in overt and covert orienting of spatial attention (e.g., Kustov & Robinson, 1996; Spence, 2014). Neurons in the superficial layers are responsive exclusively to visual stimuli, whereas over 50% of those in the deeper layers respond to more than one sensory modality stimulus and therefore categorised as multisensory (Stein & Meredith, 1993). These multisensory neurons have receptive fields (RFs) for each modality, which are in spatial register (e.g., Meredith & Stein, 1996). More importantly, if two stimuli in different modalities fall within the respective RFs of a single multisensory neuron at approximately the same time, the neuron exhibits response enhancement (i.e., increased impulses) as compared to the response to a single, unisensory stimulus (see Stein & Meredith, 1993, for a review; see also Holmes & Spence, 2005). If one of the two stimuli happens to fall outside its respective RF due to their spatial separation, however, the neuronal response is often inhibited (Meredith & Stein, 1996; Wallace et al., 1996; see also Kadunce, Vaughan, Wallace, Benedek, & Stein, 1997).

1.3. Multisensory spatial cuing

Based on the discovery of robust exogenous crossmodal spatial cuing effects and the multisensory integration resulting in response enhancement, researchers began to wonder whether multisensory (e.g., audio + tactile, or audio + visual) cues would be able to elicit larger cuing effects than unisensory (e.g., visual, auditory, or tactile) cues (Santangelo, Van der Lubbe, Belardinelli, & Postma, 2006, 2008; Spence & Driver, 1999). Disappointingly, the initial behavioural studies not only failed to document any benefit of using multisensory over unisensory cues, but also often found multisensory cuing effects to be smaller than unisensory cuing effects (see Spence & Driver, 1999). That said, it is noteworthy that while the behavioral data failed to demonstrate any advantage of using multisensory over unisensory cues, increased event-related brain potentials (ERPs) were documented from multisensory cues compared to unisensory cues (Santangelo et al., 2008). However, Santangelo and Spence (2007a) found that multisensory cues could elicit larger cuing effects than unisensory cues, when the participants were engaged in a high perceptual load task as compared to a low perceptual load task.

In Santangelo and Spence's (2007a) study, the participants performed an orthogonal spatial cuing task,[2] while monitoring a rapid sequential visual (or auditory) presentation (RSV[A]P) stream in the high perceptual load condition (see also Santangelo & Spence, 2007b). The participants in the low perceptual load condition performed only the spatial cuing task. Such findings were taken to suggest that multisensory cues are better able to

[2] The orthogonal cuing paradigm has been used in the majority of the crossmodal spatial cuing studies published to date (e.g., Ho et al., 2006; Spence & Driver, 1994, 1996, 1997a). For example, if the cues happened to be presented on the left-right dimension, the task in the orthogonal cuing design was to indicate whether the targets appeared on either on the upper vs. lower location. Therefore, the dimension of cuing is independent (or orthogonal) to that of the responses. The orthogonal cuing design allows researchers to rule out any observed performance benefits that might result simply from response priming (see Spence & Driver, 1994, 1997b; Spence & McDonald, 2004).

disengage attention from a secondary task than unisensory cues, and therefore can potentially be used as effective in-vehicle warning signals for distracted drivers (see also Santangelo, Ho, & Spence, 2008, for similar findings; see Spence & Santangelo, 2009, for a review). It is unclear, however, whether the perceptual load induced by the RSV(A)P is quantitatively and qualitatively comparable to that from real-world driving, as there is currently no objective method to measure such load (see Spence & Santangelo, 2010).

1.4. Crossmodal spatial cuing effects – current research direction and problems

Following the extensive investigation of crossmodal attention using traditional stimuli (e.g., brief pure/white noise cues; e.g., McDonald, Teder-Sälejärvi, & Hillyard, 2000; McDonald et al., 2003; Spence & Driver, 1997a), the research interest, particularly in the field of applied ergonomics, has expanded to developing in-vehicle warning signals using ecologically meaningful cues such as looming sounds. For instance, in Gray's (2011) and Ho et al.'s (2013) driving simulator studies, the efficacy of looming sounds was compared to that of other types of sound, such as constant-intensity cues, in terms of reducing the average brake RTs to potential collision events. The results of Gray's study, in particular, revealed that the participants mean brake RTs were significantly faster following the presentation of a looming sound than that of other types of sound, without resulting in increased false brake responses. It should be noted, however, that the looming sounds were presented from the vehicle dashboard and aligned centrally with the steering wheel in both studies. Therefore, their studies cannot tell us whether the presentation of a looming sound would be able to exogenously orient crossmodal spatial attention to the cued region of space more effectively than other types of sound.

According to the findings of crossmodal spatial cuing effects reported to date, providing a multisensory (e.g., auditory + visual) warning signal from the direction of potential danger on the road should provide the maximum benefit for vehicle operators. Such multisensory warning cues could be used from any direction (i.e., front, left, right, or rear space from the driver) and be able to re-orient the driver's attention to the road, even if s/he is distracted, for instance, by texting. However, it is still not clear whether the spatial specificity of crossmodal cuing effects can be applied to the design of in-vehicle warning signals to exogenously orient driver's attention to the cued region of space in any possible direction. This uncertainty exists because there is, in fact, little evidence in support of the spatial specificity of cuing effects. Most studies have investigated the topic of between-hemifield spatial cuing effects with stimuli presented in the frontal space only. Such between-hemifield spatial cuing is the default manipulation in virtually all crossmodal cuing studies that have been published to date (Feng, Störmer, Martinez, McDonald, & Hillyard, 2017; Pavani et al., 2017; Van der Stoep et al., 2015a). What is more, the within-hemifield crossmodal spatial cuing effects have been reported from a single study (Driver & Spence, 1998), only briefly reported in review papers (e.g., Spence et al., 2004; Spence & McDonald, 2004).

Furthermore, despite the findings reported in Ho and Spence's (2005) and Ho et al.'s (2006) studies, it is still unclear whether the presentation of an auditory cue would be able to exogenously orient crossmodal spatial attention to the rear space. It is important to note that the spatially nonpredictive auditory cues used in Ho and colleagues' 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 them. 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' laboratory-based driving simulator studies. What is more, in Ho and colleagues' studies, the auditory and visual stimuli presented to the rear were on the left side, whereas the frontal auditory and visual stimuli were presented from directly in front of their participants. Hence, even if the participants could not distinguish whether the auditory cues were presented from the front or rear (*front-back confusion*[3]), the presentation of an auditory cue should have been able to orient spatial attention to the cued *side* (or rather, central vs. left). As a result, their findings could simply reflect the results of the between-hemifield cuing effects (e.g., Spence & Driver, 1997a), rather than the presentation of a rear cue being able to exogenously orient spatial attention to the rear space.

1.5. Research questions to be addressed in this thesis

The fact that there is little empirical evidence in support of the spatial specificity of crossmodal cuing effects gave me the idea for the initial question for my DPhil. The first question for my DPhil that I wanted to address was, does the presentation of an auditory cue in the rear space exogenously orient crossmodal spatial attention narrowly to the cued region of space? The second question was based on the findings that the presentation of a looming sound can facilitate RTs to visual targets more than other types of sound (Gray, 2011; Ho et al., 2013). Do sound parameters, such as cue duration,

[3] Front-back confusions are common in sound localisation mainly due to the fact that the binaural cues, interaural level and time differences (ILDs and ITDs, respectively; Blauert, 1997; Grothe, Pecka, & McAlpine, 2010; Middlebrooks & Green, 1991; Schnupp, Nelken, & King, 2011), can only provide information about the likely lateral location of a sound source. As a result, sounds originating from a hypothetical cone running along the interaural axis (known as the *cone of confusion*; Shinn-Cunningham, Santarelli, & Kopco, 2000) exhibit near-identical ILDs and ITDs. Hence, based on the binaural cues, it is only possible to specify the shape of the cone of confusion from which a sound may have originated. However, the auditory system utilises spectral information to determine whether sounds originate from the front or rear, as well as their elevation (Butler & Planert, 1976; Middlebrooks & Green, 1991; Ovcharenko, Cho, & Chong, 2007; see Chapter 6, for further discussion).

intensity change (e.g., looming vs. receding intensity), or even waveform structure (e.g., triangle waveform, pure sine waveform, or broadband), modulate the crossmodal exogenous orienting of spatial attention, and if so, how?

It is important to investigate the spatial specificity of crossmodal cuing effects outside the narrow region of frontal space, before researchers can safely recommend using auditory warning signals to alert vehicle drivers to potential danger in rear space. If multisensory (e.g., auditory + tactile) warning signals are designed based on the misunderstanding of, for instance, auditory spatial cuing, each unisensory spatial cue could potentially inhibit each other, thus rendering the multisensory warning signals useless (see Meredith & Stein, 1996; Wallace et al., 1996). Therefore, investigating the first question of my DPhil will be able to provide the crucial information for the design of not only auditory warning signals, but also multisensory warning signals. The understanding of whether and, more importantly, how sound parameters modulate the crossmodal exogenous orienting of spatial attention can be vital for the design of auditory in-vehicle warning signals. Perhaps in the future, looming sounds will be used as auditory warning sounds instead of simple brief cues in order to convey information not only about the direction of potential danger on the road, but also its movement and distance. However, it is important to empirically confirm that looming sounds can elicit crossmodal spatial cuing effects first, and to test the efficacy of looming sounds compared to other types of sound.

Chapter 2. Assessing the effect of varying the stimulus onset asynchrony on audiovisual cuing effects in front and rear space

2.1. Introduction

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 leads to a short-lasting shift of attention to the cued region of space (Chapter 1; see also Spence, 2010; Spence et al., 2004, for reviews). That said, the current understanding of audiovisual spatial cuing effects is mostly based on those studies in which the auditory and visual stimuli have all been presented from frontal space. Therefore, it is unclear how localised (or narrowly focused) exogenously oriented spatial attention is, following the presentation of an auditory cue in the rear space (cf. Driver & Spence, 1998).

To the best of my knowledge, to date, no studies have investigated the potential modulatory effects of auditory cues presented in the rear space on frontal visual targets. It may seem counterintuitive to do so, however, given the published literature claiming that crossmodal exogenous cuing effects are spatially-specific, at least based on the studies using stimuli presented in the frontal space (see Chapter 1). Indeed, it has been reported that performance is fastest when auditory cues are presented from the same lateral position even within the same hemifield (Driver & Spence, 1998). Furthermore,

RTs to visual targets have been shown to increase as a function of the distance between the cue and the target (Schmitt et al., 2001). If auditory cues can be presented from either the front or rear space, the magnitude of a crossmodal spatial cuing effect ought to be larger when the cues are presented from the front (i.e., close to the target location), rather than from the rear. Nonetheless, it is crucial that such an assumption be confirmed empirically, before researchers can safely recommend using auditory warning signals to exogenously orient drivers' spatial attention to the rear (e.g., Ho & Spence, 2005, 2008, 2009; Spence & Ho, 2015).

Given the growing interest in incorporating looming sounds (with a duration of 1,000ms or longer) to vehicle warning signals (e.g., Ahtamad, Gray, Ho, Reed, & Spence, 2015; Gray, 2011; Ho et al., 2013; Chapter 1), it is also important to know whether the presentation of a looming sound can be used to exogenously orient spatial attention to the desired location. It is generally accepted that the facilitation effect from exogenously orienting spatial attention lasts for up to 300ms from the onset of an auditory cue, particularly in simple detection tasks (see Klein, 2000; see also Chapter 1). Therefore, auditory stimuli with a duration of 1,000ms or longer, no matter whether the intensity of the auditory cue increases exponentially (i.e., looming) or is constant, may be not be able to elicit any crossmodal spatial cuing effect.

Before investigating the spatial specificity of a crossmodal cuing effect using auditory cues in the front or rear space, Experiment 1 was conducted to test whether the apparatus set-up was sensitive enough to replicate the standard between-hemifield spatial cuing effect demonstrated in Spence and Driver (1997a). Experiment 2 was then designed to compare the magnitude of a crossmodal spatial cuing effect following the presentation of an auditory cue in the frontal space and that in the rear. Experiment 3, using a similar set-up as in Experiment 2, was designed to test whether the spatial cuing effects could be

documented even when auditory cues are presented for 1,000ms (i.e., when the SOA is greater than 1,000ms). The same experiment also investigated whether the dynamic change of cue intensity (i.e., looming vs. constant-intensity) would modulate the exogenous spatial cuing differently.

It was hypothesised that the presentation of an auditory cue would lead to faster RTs to visual targets presented ipsilaterally than contralaterally in Experiments 1 and 2. For Experiment 2, in particular, the hypothesis was that the magnitude of a crossmodal spatial cuing effect would be larger when the cues were presented in front than from rear space (cf. Driver & Spence, 1998; Schmitt et al., 2001). For Experiment 3, it was hypothesised that the presentation of an auditory cue with a duration of 1,000ms would not elicit any crossmodal spatial cuing effect, regardless of the cue intensity conditions.

2.2. Experiment 1

2.2.1. Methods

2.2.1.1. Participants

Eleven participants (two male and nine female)[4] with normal hearing and vision volunteered for this experiment via the Crossmodal Research Laboratory mailing list. The mean age of participants was 25 years, with a range from 19 to 31 years. The experiment lasted for approximately 40 minutes. All except one of the participants were right-handed by self-report. The participants received £5 for taking part in the study. All of the experiments reported in this thesis obtained ethical approval from the Medical

[4] A priori power analysis for sample size calculation was *not* conducted because previous crossmodal spatial cuing studies based on the orthogonal paradigm published to date had not provided effect sizes or other relevant data for such an analysis (e.g., Spence & Driver, 1997a). Therefore, for the first experiment, I stopped recruiting participants arbitrarily at the sample size of eleven.

Sciences Interdivisional Research Ethics Committee at the University of Oxford (MSD-IDREC-C1-2014-019), and were conducted following the guidelines provided.

2.2.1.2. Apparatus and materials

All experiments reported in this chapter were conducted in a darkened room (320 x 144 x 220cm), using MATLAB R2012a equipped with PSYCHTOOLBOX 3.0.10 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). In Experiment 1, a loudspeaker (M-AUDIO Studiophile AV 40; item model number: 9900-65140-00) was positioned on each side of the experimental room, behind a cloth screen onto which the visual stimuli were projected. Each loudspeaker, capable of producing frequencies between 85Hz and 20kHz, was equipped with a 1-inch diameter treble tweeter and a 4-inch diameter low frequency driver, positioned 10cm below the tweeter. The loudspeakers were placed on their sides so that the treble tweeters were situated closer to the walls than the low frequency drivers. The centre of each loudspeaker was elevated 111cm above the floor with the tweeters positioned midway between the locations of the upper and lower visual stimuli. The loudspeakers were connected to a Focusrite Scarlett 18i20 USB Computer Audio Interface (model number: AMS-SCARLETT-18i20). The screen was situated approximately 145cm from the participant's eyes.

The visual stimuli and instruction screens were projected onto a cloth screen, placed in front of the loudspeakers. The target stimuli consisted of a white circle presented against a dark background. The target was presented from one of the four positions on the projected screen: top-left, top-right, bottom-left, or bottom-right. The diameter of the circle on the screen was 13.3cm. The centres of the upper and lower visual targets were separated by 33.2cm (13.2° of vertical visual angle), while the centres of the left and right cues/targets were separated by 49.4cm (18.4° of visual angle; see Figure 2.1). The

participants were seated on a chair in the centre of the room with a backlit computer keyboard resting on their laps.

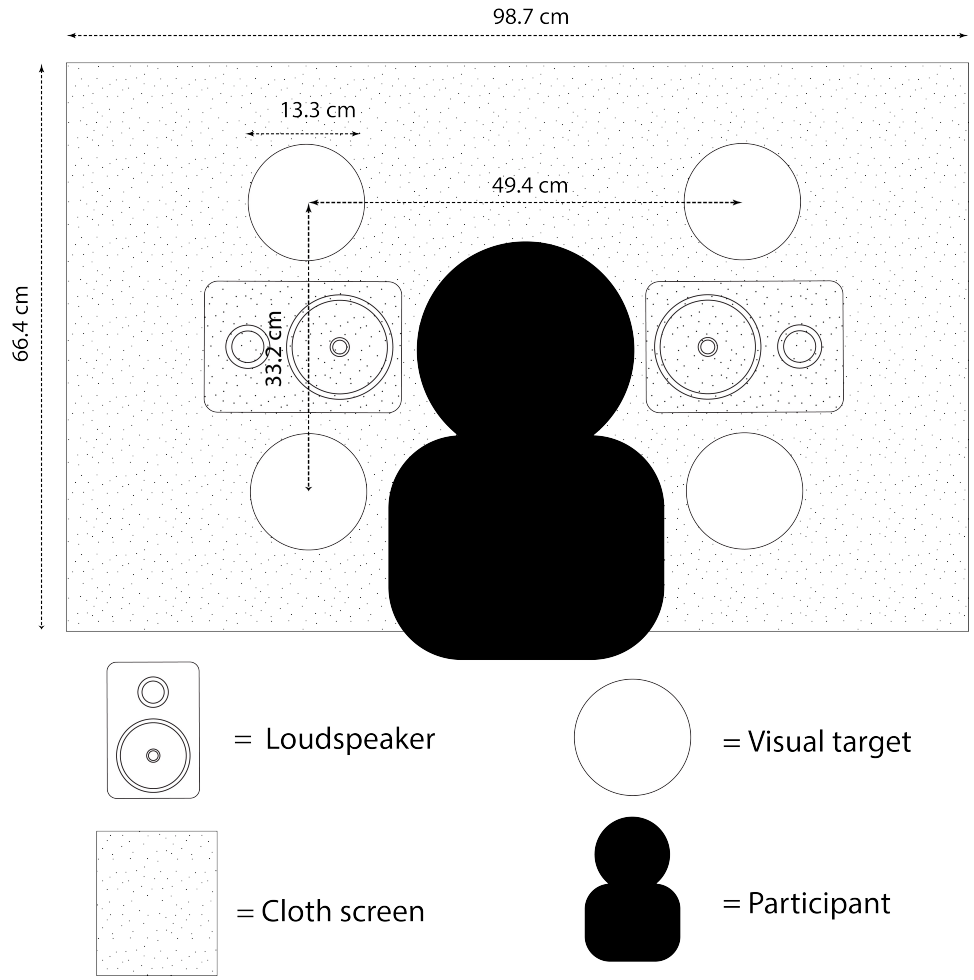


Figure 2.1. Schematic view of the loudspeaker positions behind the white cloth screen and the four possible visual target locations, as seen from behind the participant's head in Experiment 1.

2.2.1.3. Design

The experiment involved two within-participants factors: Spatial Cuing (cued if the cue and target are presented on the same side vs. uncued if not), and SOA (100, 200, 400, or 700ms). These factors were crossed to yield 8 equiprobable conditions, which occurred pseudo-randomly 24 times within each block of trials. There were four blocks of 192 trials, giving rise to a total of 768 trials per participant.

2.2.1.4. Procedure

Each trial started with the presentation of a fixation point on the screen. The fixation cross was terminated 1,000ms after its onset. Following the offset of the fixation cross, a spatially-uninformative auditory cue was presented from one of the two possible locations: front-left or front-right. The auditory cue consisted of a 50ms white noise burst presented at 80dBA, as measured from the loudspeaker location. Following the onset of the auditory cue, a visual target (a white circle) was presented on the screen for 50ms after one of the four SOAs. The participants were instructed to ignore the auditory cue and to perform the visual elevation discrimination task as rapidly and accurately as possible. The task required the participants to press the *up* arrow key on the keyboard whenever a visual target appeared on either the top-left or top-right, and to press the *down* arrow key whenever a visual target appeared on either the bottom-left or bottom-right. When the participant's key response had been registered, or else if 1,000ms had been elapsed since the onset of the visual target, the next trial started.

2.2.2. Results

First, any participants who failed to respond to over 95% of the total trials were excluded from the data analysis. This led to the removal of the data from one participant from the analysis. Second, any outliers in the RT and ER data were identified based on Tukey's (1977) method[5], and, if found, were excluded from the RT and ER data analysis. A box plot of participants' average RTs across all conditions revealed a median of 390ms, between 339 and 457ms for the 25-percentile (Q_1) and 75-percentile range (Q_3),

[5] Outliers were identified as those participants whose mean RTs across all experimental trials were faster than the lower limit or slower than the upper limit following the Tukey's (1977) method. According to Tukey, the lower limit was defined as 25-percent quartile subtracted by the interquartile range (IQR) multiplied by 1.5 and the upper limit as 75-percent quartile added by the IQR multiplied by 1.5 (see Tukey, 1977).

respectively. Another box plot of participants' average ERs in all conditions revealed a median of 1.4%, with 1.2% and 2.1% as Q_1 and Q_3, respectively. All participants' average RTs were within the lower and upper limits. One participant's average ER was above the upper limit, and was therefore excluded from the analysis. Lastly, the subsequent trials were further excluded from the remaining data: trials with incorrect responses, responses immediately following an incorrect response, no response trials, and trials with target RTs faster than 150ms. The application of the third exclusion criterion resulted in the removal of 151 trials (2.9% of the remaining data).

2.2.2.1. RT data analysis

The within-participants factors of Spatial Cuing and SOA were entered into a repeated measures analysis of variance (RM-ANOVA). The analysis revealed a significant main effect of Spatial Cuing, $F(1, 8) = 15.597$, $MSE = 36.561$, $p = .004$, $\eta_p^2 = .661$, with participants responding significantly more rapidly when the cue and target were presented on the same side (M = 403ms) than when they were presented on opposite sides (M = 408ms). There was also a significant main effect of SOA, $F(3, 24) = 7.223$, $MSE = 458.632$, $p = .001$, $\eta_p^2 = .474$, with participants responding more slowly at the shortest SOA (M = 425ms at the 100ms SOA) as compared to any of the other SOAs (M = 402, 397, and 397ms at the 200, 400, and 700ms SOAs, respectively). Note that similar findings have been reported in a number of previous studies (see Niemi & Näätänen, 1981, for the relationship between variable foreperiods and RTs; see also Spence & Driver, 1994, 1997a). There was no significant interaction. The mean RT and error rate (ER) for each condition are summarised in Table 2.1.

Table 2.1.

Mean Reaction Times (RTs) and Standard Errors (SEs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) in Experiment 1.

Spatial cuing	SOA (ms)	RTs (ms)	SEs (ms)	ERs (%)
Cued	100	420	6	0.9
	200	399	5	1.7
	400	393	5	1.7
	700	397	6	1.4
Uncued	100	431	5	1.5
	200	405	4	0.6
	400	399	3	1.5
	700	397	6	2.5

2.2.2.2. ER data analysis

A RM-ANOVA with the within-participants factors of Spatial Cuing and SOA did not yield any significant terms.

2.2.3. Discussion

The results of Experiment 1 clearly demonstrate that the presentation of a task-irrelevant peripheral white noise auditory cue leads the participants to respond more rapidly to visual targets on the same, rather than opposite, side of fixation. These findings therefore replicated the between-hemifield crossmodal spatial cuing effect (e.g., Spence & Driver, 1997a; see Spence et al., 2004, for a review), albeit with a smaller magnitude (5ms) as compared to that reported in Spence and Driver's earlier study (24ms). It should, however, be noted that the lateral separation between the centre of a visual target on one side and the fixation point was 9.2° in this experiment, as compared to 48° in Spence and Driver's study. Since the visual targets close to fixation are often detected more rapidly than those further away from fixation regardless of the cue location (this is known as the

eccentricity effect; see Carrasco et al., 1995; Carrasco & Frieder, 1997; Wolfe, O'Neil, & Bennett, 1998), the facilitation benefit from presenting the cue and target stimuli on the same side should be smaller in this experiment than in Spence and Driver's study.[6] Consequently, the more eccentric the cue and target, the greater the magnitude of any spatial cuing effects that are reported (see Chapter 4, for further discussion). It is also noteworthy that there was no two-way interaction between Spatial Cuing and SOA. The lack of the two-way interaction can be taken to suggest that crossmodal spatial cuing effects do not always dissipate after 300ms (Spence et al., 2004).[7]

Having replicated the exogenous crossmodal spatial cuing effect, I went on, in Experiment 2, to compare the magnitude of a crossmodal spatial cuing effect following the onset of an auditory cue in the frontal space and that in the rear. As stated previously, it was hypothesised that RTs to visual targets would be facilitated more following the presentation of an auditory cue on the same side than when cues were presented on the opposite side. More importantly, the second hypothesis for Experiment 2 was that the magnitude of a crossmodal spatial cuing effect would be larger when auditory cues are presented from the front than from the rear. One might expect to observe no significant crossmodal spatial cuing effect in the rear auditory cue condition, since the rear cues would always be presented from a very different location than the front targets (cf. Driver & Spence, 1998). As it should become clear, however, the magnitude of a crossmodal spatial cuing effect was the same regardless of whether auditory cues were presented from the front or rear.

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[6] Previous studies often failed to document crossmodal spatial cuing effects when the eccentricity of the visual targets was either 15° or less from the fixation (e.g., Mondor & Amirault, 1998; Ward, 1994), due possibly to the eccentricity effect. Therefore, it is noteworthy that the data from Experiment 1, with the eccentricity of 9.2° between visual targets and the central fixation, could still detect a small but significant crossmodal spatial cuing effect.

[7] Having said that, it should be noted that the mean RTs in response to visual targets at the SOA of 700ms were identical between the cued and uncued conditions (see Table 2.1).

2.3. Experiment 2

2.3.1. Methods

2.3.1.1. Participants

Twenty participants (seven male and thirteen female) were recruited for this experiment via the Crossmodal Research Laboratory mailing list.[8] All of the participants reported normal or normal-to-corrected vision, and normal hearing. The experiment lasted for approximately 40 minutes. The mean age of participants was 26 years, with a range from 18 to 40 years. All except three of the participants were right-handed by self-report. The participants received £5 for taking part in the study.

2.3.1.2. Apparatus, material, design, and procedure

These were identical to those used in Experiment 1, with the sole exception that an additional pair of loudspeakers was placed at each rear corner of the experimental room (that is, behind the participant's head). The distance between the front and rear loudspeakers was 305cm (angular distance of 161.6°; see Figure 2.2). The auditory cue was now pseudo-randomly presented from one of the four possible locations on each trial: front-left, front-right, rear-left, or rear-right. The experiment involved three within-participant factors: Cue Position (front vs. rear), Spatial Cuing (cued vs. uncued), and SOA (100, 200, 400, or 700ms). These factors were crossed to yield 16 equiprobable conditions, which were pseudo-randomly occurred 12 times within each block of trials. The participants completed a total of four blocks.

[8] The results of Experiment 1 successfully demonstrated an exogenous crossmodal spatial cuing effect based on the RT data collected from eleven participants (576 trials per participant) with a partial eta squared (η_p^2) = .661. A priori power analysis using G*Power 3 (Fault, Erdfelder, Lang, & Buchner, 2007) revealed that a sample of seven participants would provide a statistical power of 81% to detect a main effect of Spatial Cuing based on the effect size η_p^2 = .661. Therefore, a sample size of twenty and a total of 768 trials should provide enough power to detect any spatial cuing effects.

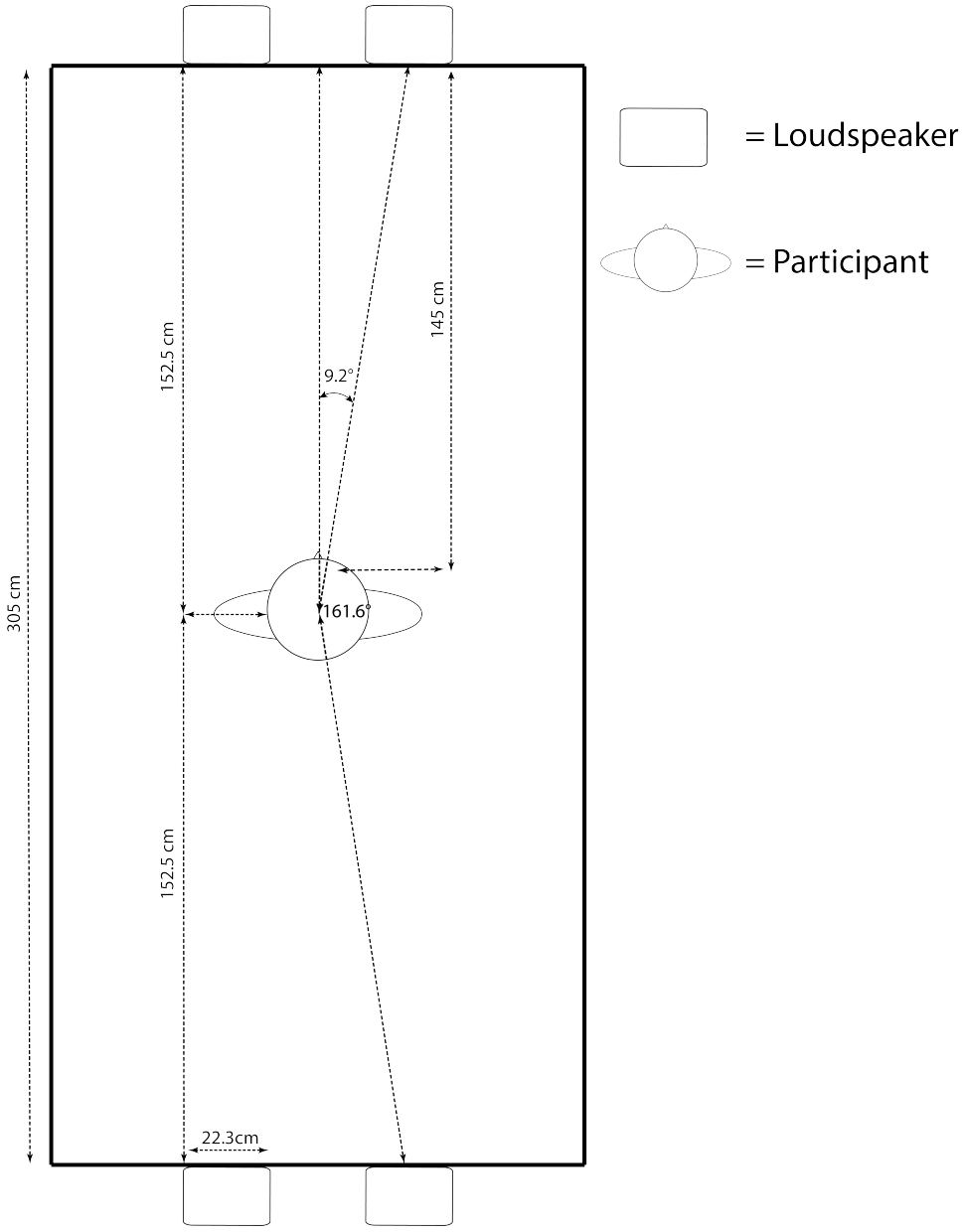


Figure 2.2. Schematic view of the loudspeaker positions behind the white cloth screen and the four possible visual target locations, as seen from behind the participant's head in Experiment 2.

2.3.2. Results

One participant failed to respond to over 95% of the total trials, and was therefore removed from the further data analysis. A box-plot of the participants' average RTs across all conditions revealed a median of 376ms, ranging from 359ms as Q_1 and 448ms

as Q_3. A box plot of participants' average ER in all conditions revealed a median of 2.0%, with 1.3% as Q_1 and 4.0% as Q_3. No outliers were identified based on Tukey's (1977) method. The application of the error response exclusion criteria used in Experiment 1 led to the removal of 794 trials (5.2% of all trials) from the data analysis.

2.3.2.1. RT data analysis

The three within-participants factors of Cue Position, Spatial Cuing, and SOA were entered into a RM-ANOVA. There was a significant main effect of Spatial Cuing, $F(1, 19) = 13.133$, $MSE = 155.664$, $p = .002$, $\eta_p^2 = .409$, with participants responding more rapidly to the targets following cues on the same (M = 395ms) rather than the opposite side (M = 400ms). There was also a significant main effect of SOA, $F(1.640, 31.154) = 9.727$, $MSE = 1322.298$, $p = .001$, $\eta_p^2 = .339$, with RTs being slower at the shortest SOA (M = 411ms at the 100ms SOA) than at the other SOAs (Ms = 396, 392, and 390ms at the SOAs of 200, 400, and 700ms, respectively). Since there was no significant interaction between Cue Position and Spatial Cuing, the results suggest that the presentation of a spatially-nonpredictive auditory cue facilitated responses to the frontal visual targets when the cue and target were presented from the same side (i.e., left or right), regardless of whether the cues were presented from the front or back. The RT and ER for each condition in Experiment 2 are summarised in Table 2.2.

Table 2.2.

Mean Reaction Times (RTs) and Standard Errors (SEs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) in Experiment 2.

Cue position	Spatial cuing	SOA (ms)	RTs (ms)	SEs (ms)	ERs (%)
Front	Cued	100	405	5	2.3
		200	394	3	2.3
		400	388	3	3.3
		700	389	4	2.0
	Uncued	100	414	4	3.9
		200	403	2	2.2
		400	396	3	3.0
		700	393	4	2.5
Rear	Cued	100	413	3	2.2
		200	394	3	3.4
		400	391	3	2.6
		700	388	4	2.1
	Uncued	100	411	4	2.0
		200	396	3	2.2
		400	397	4	3.5
		700	392	4	2.7

2.3.2.2. ER data analysis

The RM-ANOVA with the within-participants factors of Cue Position, Spatial Cuing, and SOA revealed no significant terms.

2.3.3. Discussion

The results of Experiment 2 confirmed the first hypothesis; namely, that the presentation of a task-irrelevant auditory cue would lead to faster RTs to visual targets presented ipsilaterally than contralaterally. More importantly, the presentation of a task-irrelevant white noise auditory cue facilitated participants' speeded elevation discrimination responses to visual targets presented on the same (rather than opposite) side of fixation, regardless of the front-back location of the cue (hereafter, this will be referred to as the rear-to-front crossmodal spatial cuing effect). Therefore, the second hypothesis for Experiment 2, that the spatial cuing effect would be larger when the cues were presented in front than in the rear space, was rejected. The documented rear-to-front crossmodal spatial cuing effect can be taken to support a rather surprising conclusion, namely that the exact co-location of auditory cues and visual targets is by no means necessary to elicit a significant crossmodal spatial cuing effect. Instead, it would seem that the presentation of an auditory cue on the left or right side gives rise to a lateralised shift of visual attention regardless of the exact location from which that cue happens to be presented.

It is worth pausing for a moment to note that the lateral separation between the rear cue and the frontal target on the same side was approximately 160°, whereas the frontal cue and the frontal target on the same side were separated only by approximately 18°. Yet, RTs to frontal targets were significantly (although slightly[9]) faster following the presentation of a rear auditory cue on the same side as the targets than that of a frontal

[9] The magnitude of the spatial cuing effect was rather small (5ms) in Experiment 2, as in Experiment 1, possibly due to the placement of the visual targets and the eccentricity effect (see Carrasco et al., 1995; Carrasco & Frieder, 1997). Even though the facilitation benefit in RTs from exogenous spatial cuing may seem trivial, it is worth remembering that the magnitude of facilitation would likely increase if the cues were to be made spatially-informative (see Ho & Spence, 2005). Therefore, any crossmodal spatial cuing effects in the laboratory setting, whether the magnitudes are large or small, can be effective, if applied, in the real-life driving situations.

auditory cue on the opposite side from the targets. Perhaps the simplest explanation for the null effect of Cue Position (i.e., front vs. rear) would be to suggest that the participants erroneously heard the rear auditory cues as coming from the frontal loudspeakers. In other words, some sort of front-back confusion could have led to the documented rear-to-front crossmodal spatial cuing effect (cf. Spence, 2013; Spence & Driver, 2000; see also Footnote 3 in Chapter 1). However, it is unlikely that the participants experienced any such front-back confusion, since the white noises are considered to be easy to localise (see Spence & Driver, 2000).

The data analysis once again revealed that there was no two-way interaction between Spatial Cuing and SOA. The lack of two-way interaction in both Experiments 1 and 2 would appear to suggest that significant spatial cuing effects can last up to 700ms at least in target elevation discrimination tasks involving auditory cues and visual targets. Will the presentation of an auditory cue with a duration of 1,000ms still be able to elicit a crossmodal spatial cuing effect? Experiment 3 was conducted in order to investigate this question.

2.4. Experiment 3

2.4.1. Methods

2.4.1.1. Participants

Eleven participants (three male and eight female) were recruited to take part in this study through the Crossmodal Research mailing list. All but one reported that they were right-handed. All of the participants reported normal (or normal-to-corrected) vision and hearing. The experiment took approximately 30 minutes to complete. The mean age of

participants was 26 years, ranging from 19 to 32 years. The participants received £5 at the end of the experiment for taking part in the study.

2.4.1.2. Apparatus, materials, design, and procedure

The apparatus, materials, and procedure were identical to those used in Experiment 2, except the two types of auditory stimuli that were used as auditory cues: looming and constant-intensity. Both consisted of white noise presented for 1,000ms. The looming cue exponentially ramped up in intensity from silence to 80dBA as measured from the loudspeaker to imitate the intensity change of an object approaching the observer at a speed of 49.05m/s. The constant-intensity cue, on the other hand, was presented at 80dBA as measured from the loudspeaker. Following the *offset* of the auditory cue, the target circle appeared at one of three interstimulus intervals[10] (ISIs; 50, 150, or 400ms) for 200ms (up from 50ms in Experiment 2). There were four within-participants factors: Cue Position (front vs. rear), Cue Type (looming vs. constant-intensity), Spatial Cuing (cued vs. uncued), and ISI (50, 150, or 400ms). Taken together, these factors gave rise to a total of 24 conditions. The procedure was identical to that of Experiment 2. Twenty-four conditions were randomised on a trial-by-trial basis, and each participant completed a total of 300 trials in a single block.

2.4.2. Results

All of the participants responded to more than 95% of all trials. A box plot of participants' average RTs across all conditions revealed a median of 392ms, ranging from 359ms (Q_1) to 421ms (Q_3). A box plot of participants' average ERs across all

[10] Note that SOAs were extended to more than 1,000ms due to the duration of the cue. Because of the extensive gap between the onset and offset of the auditory cue, the SOAs in Experiment 3 are expressed as ISIs.

conditions revealed a median of 1.3%, ranging from 0.7% (Q_1) to 2.8% (Q_3). One participant's average RT across all conditions (M = 607ms) was greater than the upper limit, and was therefore removed from the subsequent data analyses (see Tukey, 1977). The application of the same exclusion criteria from Experiments 1 and 2 resulted in the removal 120 trials (4.0% of all trials).

2.4.2.1. RT data analysis

The within-participants factors of Cue Position, Cue Type, Spatial Cuing, and ISI were entered into a RM-ANOVA. The analysis revealed a significant main effect of Cue Type, $F(1, 9) = 15.482$, $MSE = 1434.147$, $p = .003$, $\eta_p^2 = .632$, with participants responding more rapidly following the presentation of a looming cue (M = 377ms) than following the presentation of a constant-intensity cue (M = 396ms). A significant main effect of Spatial Cuing was obtained, $F(1, 9) = 10.447$, $MSE = 537.932$, $p = .010$, $\eta_p^2 = .537$. The participants responded significantly more rapidly on the cued trials (M = 383ms) than on the uncued trials (M = 391ms). There was a significant main effect of ISI, $F(2, 18) = 8.735$, $MSE = 1352.732$, $p = .002$, $\eta_p^2 = .493$, with participants responding more slowly at the shortest ISI (M = 400ms) as compared to either of the other intervals (M = 381 and 380ms at the 150ms ISI and 400ms ISI, respectively). A significant two-way interaction was found between Cue Position and Cue Type, $F(1, 9) = 14.309$, $MSE = 311.656$, $p = .004$, $\eta_p^2 = .614$. The interaction was attributable to the significantly faster RTs to visual targets following the presentation of a looming cue than a constant cue in the front (with the magnitude of 28ms), $t(9) = -5.425$, $p < .001$, than in the rear (with the magnitude of 11ms), $t(9) = -2.843$, $p = .019$.

There was a significant three-way interaction between Cue Position, Cue Type, and Spatial Cuing, $F(1, 9) = 5.511$, $MSE = 599.100$, $p = .043$, $\eta_p^2 = .380$. In order to break down the interaction, two separate RM-ANOVAs were conducted, one for each Cue Position condition. The analysis with the front cue condition revealed a significant main effect of Cue Type, $F(1, 9) = 27.976$, $MSE = 269.865$, $p = .001$, $\eta_p^2 = .757$ and a significant main effect of Spatial Cuing, $F(1, 9) = 17.557$, $MSE = 56.081$, $p = .002$, $\eta_p^2 = .661$. More importantly, there was a significant two-way interaction between Cue Type and Spatial Cuing, $F(1, 9) = 13.141$, $MSE = 46.979$, $p = .006$, $\eta_p^2 = .594$. Paired *t*-tests with Bonferroni correction ($\alpha = .025$) revealed that in the looming auditory cue condition, the participants responded significantly more rapidly when the cue and target were presented ipsilaterally (M = 366ms) than when they were presented contralaterally (M = 384ms), $t(9) = -5.063$, $p = .001$. However, in the constant-intensity cue condition, no spatial cuing effects were observed, $t(9) = -.718$, $p = .491$. Another RM-ANOVA for the rear cue condition with Cue Type and Spatial Cuing only revealed a main effect of Cue Type, $F(1, 9) = 7.250$, $MSE = 164.785$, $p = .025$, $\eta_p^2 = .446$. Furthermore, the analysis revealed no significant interaction term ($p = .266$), and, more importantly, no spatial cuing effect ($p = .084$). The RT and ER for each condition in Experiment 3 are summarised in Table 2.3.

Table 2.3.

Mean Reaction Times (RTs) and Standard Errors (SEs) in milliseconds and Mean Error Rates (ERs) in percentages (%) in Experiment 3.

Cue position	Spatial cuing	ISI (ms)	Looming-intensity			Constant-intensity		
			RTs (ms)	SEs (ms)	ERs (%)	RTs (ms)	SEs (ms)	ERs (%)
Front	Cued	50	386	9	1.6	419	10	0.8
		150	362	8	2.8	398	6	1.7
		400	359	6	2.5	378	8	1.6
	Uncued	50	393	8	1.6	415	8	2.9
		150	384	8	4.5	398	9	0.7
		400	379	7	0.8	403	9	1.5
Rear	Cued	50	390	12	1.6	396	9	2.7
		150	376	6	4.8	387	7	1.9
		400	373	6	3.1	377	8	0.8
	Uncued	50	391	9	3.2	412	10	0.7
		150	361	7	3.6	392	7	1.8
		400	386	6	0.8	382	5	1.6

2.4.2.2. ER data analysis

The RM-ANOVA with the within-participants factors of Cue Position, Cue Type, Spatial Cuing, and ISI did not yield any significant terms.

2.4.3. Discussion

The analysis of the data from Experiment 3 revealed that when the looming cue was presented from the front, RTs to the frontal visual targets were significantly faster when the cue and target were presented ipsilaterally than when they were presented contralaterally. The presentation of a looming cue from the rear did not elicit a rear-to-front crossmodal spatial cuing effect, unlike that of a 50ms constant-intensity cue as used in Experiment 2. On the other hand, the constant-intensity cues with a duration of 1,000ms in this experiment failed to elicit any significant crossmodal facilitation, no matter whether they were presented from the front or rear space. Therefore, the results of Experiment 3 failed to confirm the hypothesis in the looming auditory cue condition. Namely, that the presentation of a looming auditory cue, but not a constant-intensity cue, could still elicit a significant crossmodal spatial cuing effect past the SOA of 1,000ms.

The interesting finding in Experiment 3, perhaps more than the documented spatial cuing effect after the 1,000ms SOA, is that the presentation of a looming cue facilitated the perception of visual targets only when presented in frontal space. The documented rear-to-front crossmodal spatial cuing effect in Experiment 2 suggests that the presentation of a brief (and constant-intensity) auditory cue would give rise to a lateralised shift of participant's spatial attention. The crossmodal spatial cuing effect documented in Experiment 3, on the other hand, indicates that the onset of a 1,000ms looming auditory cue can exogenously orient spatial attention narrowly to the cued region of space. Therefore, unexpectedly, the hypothesis that was initially intended for Experiment 2 would appear to be confirmed when auditory cues consist of a looming white noise. Namely, the magnitude of a crossmodal spatial cuing effect is larger when the looming white noise cues are presented in front than in rear space.

It is also noteworthy that the magnitude of RT facilitation from looming cues in Experiment 3 (18ms) was greater than that from short burst white noises in Experiments 1 and 2 (5ms), despite the same cue and target eccentricity (see Gray, 2011, for similar findings in a driving simulation study; see also Carrasco et al., 1995, for how stimulus eccentricity influences RTs to target stimuli). Furthermore, if the participants perceived the rear looming cues as presented from the front, the rear looming cues should also have facilitated RTs to the frontal visual targets. Therefore, the possibility of front-back confusion can be ruled out for such a spatially-specific crossmodal cuing effect from the looming cues. In summary, the findings of Experiment 3 suggest that looming sounds can engage spatial attention for longer and more narrowly to the cued region of space than other types of auditory cues (e.g., 50ms burst white noises or 1,000ms constant-intensity cues).

2.5. General discussion

The crossmodal (audiovisual, in particular) attention research literature published to date has documented a number of findings. First of all, the presentation of a spatially-uninformative auditory cue can exogenously orient crossmodal attention to the cued region of space, resulting in faster RTs to visual targets presented ipsilaterally than to those presented contralaterally (Spence & Driver, 1997a; see also Spence et al., 2004; Spence & McDonald, 2004, for reviews). Second, RTs to visual targets are fastest when cues and targets are presented from the same position, and RTs tend to increase as a function of the increasing distance between the cue and target (Driver & Spence, 1998; Schmitt et al., 2001). In other words, crossmodal cuing effects are spatially-specific. Lastly, crossmodal facilitation effects last for approximately around 300ms from the onset of an auditory cue. The findings are, however, mostly based on the studies that

have only ever presented stimuli in frontal space, with brief auditory cues typically lasting for 100ms or less (e.g., McDonald et al., 2003; Spence & Driver, 1997a). The experiments reported in this first experimental chapter were designed to investigate whether the current understanding of crossmodal spatial cuing effects based on the limitations listed above could be generalised to the rear space and other types of sound.

The existence of crossmodal spatial cuing effects was confirmed in Experiments 1 and 2. Perhaps one of the most interesting findings to emerge from the experiments reported in this chapter was that the presentation of a brief (i.e., 50ms) auditory cue elicited a crossmodal spatial cuing effect for frontal visual targets, regardless of the front-back location of the cue (Experiment 2). The documented rear-to-front crossmodal spatial cuing effect, therefore, contradicted the spatial specificity of crossmodal exogenous orienting. However, the spatial specificity of crossmodal exogenous attentional cuing was, rather unexpectedly, confirmed in the condition in which looming auditory cues with a duration of 1,000ms were used (Experiment 3).[11] The crossmodal cuing effect documented in all three experiments also provided evidence against the claim that such facilitation effects last for about 300ms from the onset of a cue (Chapter 1; also see Fuentes & Campoy, 2008, for a similar result). In short, all but one of the hypotheses (namely, that RTs to targets would be faster when the cue and target were presented on the same, rather than opposite, side) were not confirmed.

To the best of my knowledge, no studies have investigated whether the presentation of an auditory cue in the rear space would modulate spatial attention in the frontal space. Therefore, it is unclear whether the rear-to-front crossmodal spatial cuing effect

[11] I realise now that the perceived duration of the looming cue, unlike that of the constant-intensity cue, must actually have been less than 1,000ms since the onset intensity of a looming cue was 0 dBA (see Sabin, Macpherson, & Middlebrooks, 2005). Therefore, the lack of a crossmodal spatial cuing effect following the presentation of a constant-intensity cue could have been entirely attributable to the longer perceived duration and, as a result, SOAs than in the looming auditory cue condition.

documented in Experiment 2 is a robust empirical phenomenon or not. In fact, it is worth remembering that the magnitude of the crossmodal spatial cuing effect was only 5ms in Experiments 1 and 2, compared to over 20ms reported in Spence & Driver (1997a). Therefore, it is possible that the current apparatus set-up (e.g., separation of 9.2° between the visual targets and the central fixation) was not sensitive enough to detect a two-way interaction between Cue Position and Spatial Cuing. Who knows if the lateral separation between the visual targets and central fixation was wide enough to detect a large crossmodal spatial cuing effect (e.g., Spence & Driver, 1997a), the difference between the cuing effect from the cues presented in front and that in the rear space might have been able to reach statistical significance. Before jumping to any conclusion, though, the next logical step would be to continue investigating the spatial specificity of crossmodal exogenous cuing effect by trying and replicating the rear-to-front crossmodal spatial cuing effect in Chapter 3.

Chapter 3. Audiovisual crossmodal cuing effects in front and rear space

3.1. Introduction

The results of Experiment 2 revealed that the presentation of an auditory cue (with a duration of 50ms) elicited faster responses to frontal visual targets presented ipsilaterally than contralaterally, regardless of whether the cue was presented from the front or back. Since the rear cue and frontal target on the same side were presented from very different locations (separated by approximately 160° in the horizontal plane), such a finding would seem to contradict the purported spatial specificity of the crossmodal cuing effect (Driver & Spence, 1998; Schmitt et al., 2001; see Spence et al., 2004, for a review). In comparison to the findings of Experiment 2, the presentation of a looming cue with a duration of 1,000ms gave rise to faster RTs to targets presented ipsilaterally as compared to contralaterally, without eliciting a rear-to-front crossmodal spatial cuing effect (Experiment 3). Therefore, the current understanding of audiovisual spatial cuing obtained in frontal space at least when brief auditory cues were presented cannot be generalised to such cues presented from the rear. However, the spatial specificity of the exogenous crossmodal cuing effect appears to hold true when looming auditory cues with a duration of 1,000ms are used to exogenously orient visual attention.

Before concluding that the presentation of a brief rear auditory cue can modulate visual attention in front space, however, it is undoubtedly important to first try and replicate the rear-to-front crossmodal spatial cuing effect that was reported in Experiment 2. After all, to the best of my knowledge, the rear-to-front crossmodal spatial cuing effect has been

documented in just a single experiment.[12] Such a result, if replicable, may well have important implications for the design of rear auditory warning signals (e.g., alarms for vehicles in blind spots). In order to maximise the chance to detect the two-way interaction between Cue Position and Spatial Cuing (see Chapter 2), the visual angle between the left and right target positions has been increased to 90° in the new set-up (from 18.4° in Chapter 2). In order to test the sensitivity of the new set-up in detecting any spatial cuing effects, Experiment 4 was conducted as a replication study of Experiment 1 and Spence and Driver's (1997a), Experiment 1. The hypothesis for Experiment 4 was that participants would respond significantly faster (and possibly also more accurately) to visual targets preceded by cues from the same side of central fixation as compared to those presented on the opposite side. Then, Experiment 5 was conducted as a replication study of Experiment 2, with two loudspeakers added to the new apparatus set-up used in Experiment 4. Lastly, in Experiment 6, a sound location discrimination study was conducted in order to investigate the important issue of whether rear-to-front crossmodal spatial cuing effects could be attributable to some kind of front-back confusion.

In addition to the within-participants factors examined in Experiment 1, Cue Type (pure tone or white noise) factor was added into the design of Experiment 4 in order to investigate whether the bandwidth of auditory cues would modulate spatial attention. Although white noise stimuli are easier to localise than pure tones in the vertical plane and in the front-back dimension (see Spence & Driver, 2000), sound localisation

[12] There is currently a great deal of concern regarding the replication crisis in psychology (not to mention other disciplines; see Kaiser, 2017). Recent findings suggest that less than 20% of 'surprising' results can be reproduced (see Francis, 2014; also see Doyen, Klein, Pichon, & Cleeremans, 2012; Steele, 2014; Yong, 2012). Furthermore, more than half of the 100 findings in psychology could not be replicated in the recent reproducibility test (Baker, 2015; though see also Baker, 2016). Therefore, the importance of a successful replication of the rear-to-front crossmodal spatial cuing effect reported in Experiment 2 (Chapter 2) should not be underestimated.

performance in the horizontal plane is relatively robust regardless of the bandwidth (see Hofman & Van Opstal, 1998). Therefore, it was hypothesized that the magnitude of a crossmodal spatial cuing effect would not be different between the white noise cue condition and the pure tone cue condition.

3.2. Experiment 4

3.2.1. Methods

3.2.1.1. Participants

Twenty participants (ten male and ten female) volunteered for Experiment 4 through the Crossmodal Research Lab mailing list and Oxford Psychology Research (OPR) participant recruitment scheme. The average age of the participants was 26 years, with a range from 19 to 37. All of the participants were right-handed, and had normal hearing and vision, by self-report. The experimental session lasted for approximately 30 minutes. The participants were paid £5 in return for taking part in the study.

3.2.1.2. Apparatus and materials

All of the experiments reported in this chapter were conducted in a darkened room (320 x 144 x 220cm), using MATLAB R2012a with PSYCHTOOLBOX 3.0.10 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). The participants were seated at a desk with a backlit computer keyboard, approximately 60cm away from a cloth screen mounted on the front wall of the room. The cloth screen hid five 12v 5mm LEDs with a luminance of 8000 millicandelas and two same loudspeakers used in Chapter 2. The LEDs were controlled by an Arduino Uno board rev.3, following MATLAB commands. One LED was placed at the centre of the screen, approximately at the eye level of the participants

(111cm from the floor) as a fixation point. Four additional LEDs were installed to be used as visual targets in the top-left, top-right, bottom-left, and bottom-right positions, each separated by 120cm horizontally (i.e., 90° of visual angle) and by 80cm vertically (i.e., 67.4° of visual angle) with the fixation LED positioned in the centre directly in front of the participants (see Figure 3.1).

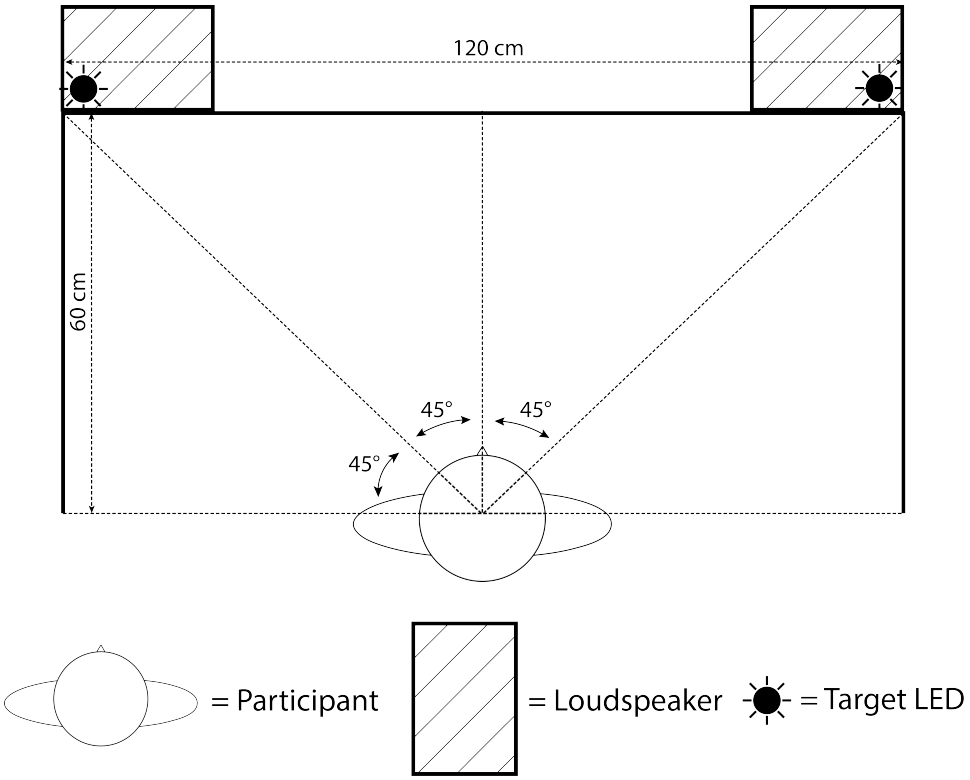


Figure 3.1. Bird's-eye view highlighting the position of the loudspeakers and target LEDs in relation to the participant in Experiment 4.

The loudspeakers were placed on their sides as in Experiments 1-3. The loudspeakers were connected to the same USB audio interface used in Experiments 1-3. The farthest sides of the two loudspeakers were separated by a distance of 120cm. The centre of each treble tweeter and low frequency driver was placed 111cm above the floor. The auditory cues consisted of a 2kHz pure tone at 75dBA and white noise (with a frequency cut-off range between 0 and 22kHz) presented at 68dBA, both measured from the participant's

ear position.[13] The sample rate for both auditory cues was 44.1kHz. A computer monitor (Dell UltraSharp; model 1908FPb) was placed on the left side of the participant's seat to display instruction screens.

3.2.1.3. Design

There were three within-participants factors in the experiment: Cue Type (pure tone vs. white noise), Spatial Cuing (cued vs. uncued), and SOA (100, 200, or 700ms). The crossing of these factors yielded 12 possible conditions, with each condition being presented 12 times pseudo-randomly in each block of 144 trials. The participants completed a total of three blocks, and were encouraged to take a short break between blocks.

3.2.1.4. Procedure

At the start of each trial, the fixation LED was illuminated and remained illuminated for 2,000ms after the onset of the visual target, or until the participant made a response. After a random delay of 400-650ms (selected from the discrete uniform distribution) following the onset of the fixation, an auditory cue was presented for 100ms from one of the two loudspeakers at a constant intensity. Depending on the condition of SOA, a visual target was then presented as the illumination of one of the four LEDs for 140ms, 100, 200, or 700ms after the onset of the auditory cue. The participants were instructed to press the *up* arrow key on the keyboard if an LED illuminated on either the upper-left or upper-right, and to press the *down* arrow key if an LED illuminated on either the lower-left or lower-right. The participants were further instructed to ignore the auditory

[13] The two types of auditory cue were presented at different volumes due to the technical difficulties associated with matching them exactly.

cue, and to respond as rapidly and accurately as possible to the location of the visual target. If the participants failed to respond within 2,000ms from the onset of the visual target, the trial terminated and the next trial began. While I was still in the experiment room, the participants completed 10 practice trials. Upon the completion of the practice trials, the participants were given a chance to ask any questions. Once their questions had been answered, I stepped out of the experiment room and closed the door before they proceeded to the actual trial.

3.2.2. Results

Three participants failed to respond to over 95% of the total trials and were therefore excluded from the data analysis. A box plot of participants' average RTs across all conditions revealed a median of 405ms, between 350ms as Q_1 and 485ms as Q_3. Another box plot of participants' average ERs in all conditions revealed a median of 1.6%, between 0.5% as Q_1 and 3.2% as Q_3. All participants' average RTs and ERs were within the lower and upper limits; no outlier was identified based on the Tukey's (1977) method. Lastly, the subsequent trials were further excluded from the remaining data: trials with incorrect responses, responses immediately following an incorrect response, no response trials, and trials with target RTs slower than 1,500ms or faster than 150ms. The application of the third exclusion criterion resulted in the removal of 307 trials (4.2% of the remaining data).

RT data analysis

A RM-ANOVA was conducted with the within-participants factors of Cue Type, Spatial Cuing, and SOA. The analysis revealed a significant main effect of Spatial Cuing, $F(1, 16) = 43.639$, $MSE = 372.400$, $p < .001$, $\eta_p^2 = .732$, with participants responding more

rapidly on the cued trials (M = 406ms) than on the uncued trials (M = 425ms). Therefore, the results of Experiment 4 confirmed my first hypothesis that the presentation of an auditory cue would facilitate responses to visual targets presented ipsilaterally as compared to those presented contralaterally. There was also a significant main effect of SOA, $F(2, 32) = 26.539$, $MSE = 419.313$, $p < .001$, $\eta_p^2 = .624$, with participants responding more slowly at the 100ms (M = 429 ms) as compared to either the 200ms (M = 411ms) or 700ms (M = 405ms) SOAs.

The two-way interaction between Cue Type and Spatial Cuing was significant, $F(1, 16) = 5.259$, $MSE = 189.224$, $p = .036$, $\eta_p^2 = .247$. The interaction was attributable to the magnitude of a spatial cuing effect in the pure tone cue condition (M = 22ms) being significantly larger than that in the white noise cue condition (M = 13ms), $t(16) = -2.294$, $p = .036$. The results of Experiment 4 therefore failed to confirm my second hypothesis that the magnitude of a spatial cuing effect will not be different between the white noise cue condition and the pure tone cue condition. The analysis of the data also highlighted a significant two-way interaction between Spatial Cuing and SOA, $F(2, 32) = 5.602$, $MSE = 116.639$, $p = .008$, $\eta_p^2 = .259$. The interaction occurred due to the decreased magnitude of the spatial cuing effect as a function of the increasing SOA. Paired sample *t*-tests at each SOA with Bonferroni correction ($\alpha = .0167$) revealed that the spatial cuing effects were all significant at the 100ms ($p < .001$), 200ms ($p < .001$), and 700ms SOAs ($p = .004$; see Figure 3.2). The mean RTs and ERs for each condition In Experiment 4 are summarised in Table 3.1.

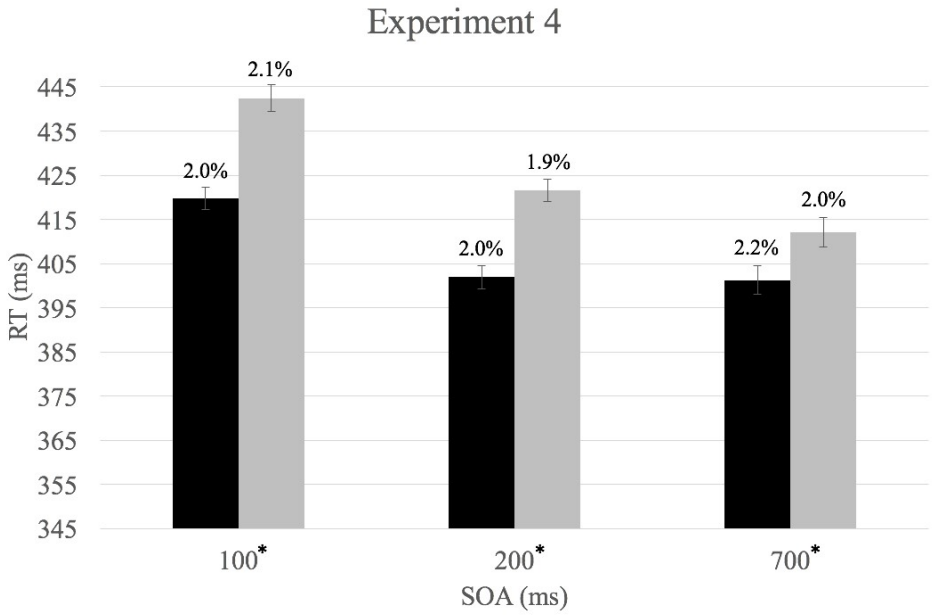


Figure 3.2. Mean reaction times (RTs) in milliseconds (ms) and mean error rates (ERs) in percentages (%) as a function of cue-target SOA in Experiment 4. Black and grey bars represent the mean RTs in the cued condition and those in the uncued conditions, respectively. Standard errors of the mean RTs are indicated by the vertical lines. Asterisks indicate significant spatial cuing effects from the RT data analysis at given SOAs based on paired sample *t*-tests with Bonferroni correction ($p < .0167$).

Table 3.1.

Mean Reaction Times (RTs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) from the pure tone and white noise conditions as a function of SOA and Spatial Cuing in Experiment 4.

		Pure tone		White noise	
SOA (ms)	Spatial cuing	RT (ms)	ER (%)	RT (ms)	ER (%)
100	Cued	423	1.5	417	2.5
	Uncued	444	2.2	440	2.1
200	Cued	400	2.3	406	1.6
	Uncued	423	2.1	421	1.6
700	Cued	398	2.3	406	2.1
	Uncued	418	2.3	408	1.8

ER data analysis

An equivalent RM-ANOVA on the ER data did not reveal any significant terms.

3.2.3. Discussion

The results of Experiment 4 demonstrated a significant exogenous crossmodal cuing effect. In particular, the participants' RTs in response to visual targets were facilitated when the cue and target were presented from the same, rather than different, side of central fixation. These results therefore successfully replicated the findings of Experiment 1 and those reported some years ago by Spence and Driver (1997a; see Spence et al., 2004, for a review). However, an interesting result to emerge from the analysis of the data from Experiment 4 was that the magnitude of the crossmodal cuing effects was larger in the pure tone cue condition than in the white noise cue condition. I suspect that the alerting effect might have interacted with the exogenous crossmodal spatial cuing due to the greater intensity of the pure tone than white noise auditory cues (see Petersen & Posner, 2012).

Having confirmed the existence of exogenous crossmodal spatial cuing effects for the second time, I went on to test whether it would be possible to replicate the rear-to-front crossmodal spatial cuing effect reported in Experiment 2 (Chapter 2). The design of Experiment 5 was identical to that of Experiment 4, except that an auditory cue could be presented pseudo-randomly from one of the four possible locations on each trial: front-left, front-right, rear-left, or rear-right. My first hypothesis was that the presentation of an auditory cue would facilitate RTs to frontal visual targets presented ipsilaterally as compared to contralaterally. I further hypothesised, as in Experiment 2, that the spatial cuing effect would be larger when the cues were presented from the front than from the rear; no rear-to-front crossmodal spatial cuing effect would be documented.

3.3. Experiment 5

3.3.1. Methods

3.3.1.1 Participants

Twenty-five participants (eleven men and fourteen women) were recruited for Experiment 5 from the same two sources used for Experiment 4, as well as from the Oxford University Experimental Psychology Research Participation Scheme (RPS). The mean age of the participants was 26 years, ranging from 20 to 41 years. There were twenty-three right-handed, one left-handed, and one ambidextrous participant by self-report. At the end of the study, the participants were either given two course credits or else £5 for taking part in this experiment.

3.3.1.2 Apparatus and materials

The apparatus was identical to that used in Experiment 4, with the sole exception that an additional pair of loudspeakers was now placed behind the participant's seat, parallel to the front loudspeakers. The distance between the front and rear loudspeakers was the same as that between the left and right loudspeakers: 120cm, with each loudspeaker situated approximately 85cm from the participants at 315° to front-left, 45° to front-right, 225° to rear-left, or 135° to rear-right position, with the central fixation LED located approximately at 0° in azimuth and in the vertical plane (see Figure 3.3).

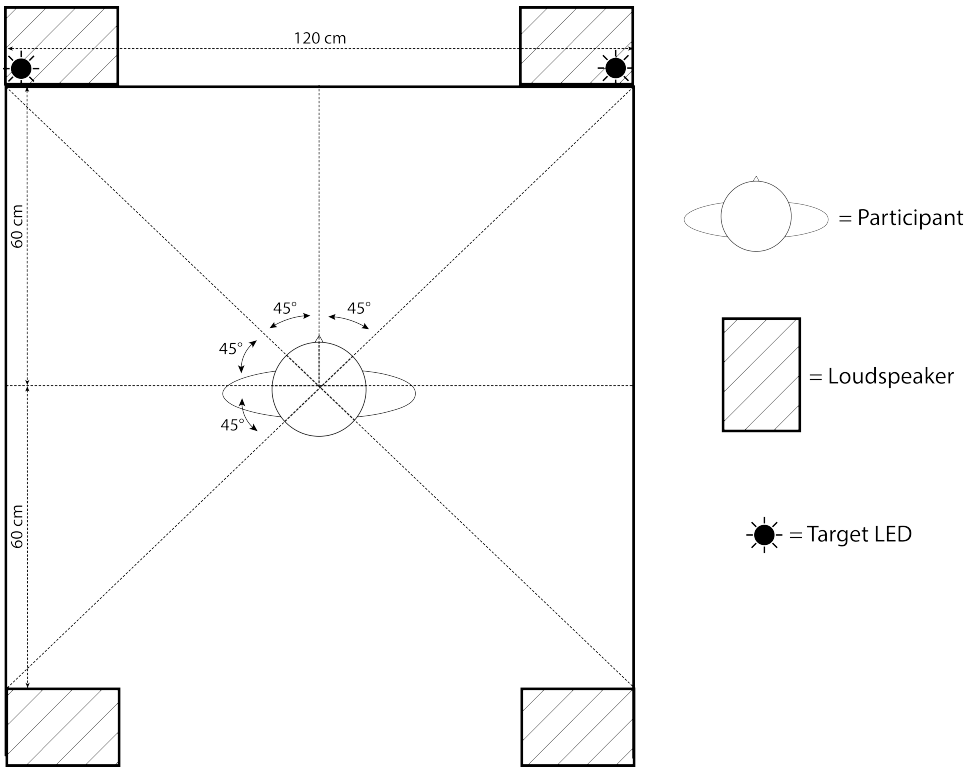


Figure 3.3. Schematic bird's-eye view of the position of the loudspeakers and target LEDs in relation to the participant in Experiment 5.

3.3.1.3 Design and procedure

These were the same as in Experiment 4, with the sole exception that an additional within-participants factor, Cue Position (front vs. rear), was added to the experimental design. Hence, in each trial, an auditory cue could be presented either from front-left, front-right, rear-left, or rear-right location. This gave rise to a total of 24 possible conditions, with each condition occurring 6 times in a random order, once again giving rise to a total of 432 trials in three blocks.

3.3.2. Results

All participants responded to more than 95% of the trials. The median of the participants' average RTs across all conditions was 416ms, with 361ms as Q_1 and 437ms as Q_3. The median of the participants' average ERs in all conditions was 1.2%, with

0.5% and 2.3% as Q_1 and Q_3, respectively. One participant's average ER (6.5%) was above the upper limit (5.1%) based on the Tukey's (1977) method, and was therefore removed from the data analysis. A total of 272 trials (2.6%) were removed based on the exclusion criteria used in Experiment 4.

RT data analysis

A RM-ANOVA with the within-participants factors of Cue Position (front vs. rear), Cue Type, Spatial Cuing, and SOA once again revealed a significant main effect of Spatial Cuing, $F(1, 23) = 25.781$, $MSE = 711.139$, $p < .001$, $\eta_p^2 = .529$, with participants responding significantly more rapidly when the targets were presented from the same side as the cue (M = 402ms) than when the cue and target were presented from opposite sides (M = 413ms). The analysis also revealed a significant main effect of SOA, $F(1.244, 28.610) = 17.400$, $MSE = 1996.601$, $p < .001$. $\eta_p^2 = .431$. As in Experiment 4, the participants responded more slowly to those targets presented at the shortest SOA (M = 419ms) than at the other, longer, SOAs (Ms = 402ms and 401ms for the 200ms SOA and the 700ms SOA, respectively). A significant interaction was found between Cue Position and SOA, $F(2, 46) = 4.117$, $MSE = 203.382$, $p = .023$, $\eta_p^2 = .152$. The interaction was due to the participants responding 3ms faster in the rear cue position condition than in the front cue position condition at the 100ms SOA, whereas the RTs were faster in the front cue position condition than in the rear cue position condition at the 200ms SOA (by 3ms) and the 700ms SOA (by 4ms). The mean RT and ER for each condition in Experiment 5 are summarised in Table 3.2.

Table 3.2.

Mean Reaction Times (RTs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) from the pure tone and white noise conditions as a function of Cue Position, SOA, and Spatial Cuing in Experiment 5.

			Pure tone		White noise	
Cue position	SOA	Spatial cuing	RT (ms)	ER (%)	RT (ms)	ER (%)
Front	100 ms	Cued	417	0.7	413	0.5
		Uncued	427	1.9	428	3.3
	200 ms	Cued	393	0.7	390	1.6
		Uncued	411	1.4	409	0.5
	700 ms	Cued	399	1.6	395	2.1
		Uncued	405	0.7	395	0.9
Rear	100 ms	Cued	411	1.4	411	0.9
		Uncued	419	1.9	432	1.2
	200 ms	Cued	399	1.6	398	0.5
		Uncued	409	2.3	407	1.2
	700 ms	Cued	400	0.7	396	1.6
		Uncued	405	1.9	410	0.2

ER data analysis

An equivalent RM-ANOVA on the ER data revealed a significant two-way interaction between Cue Position and Cue Type, $F(1, 23) = 6.692$, $MSE = .001$, $p = .016$, $\eta_p^2 = .225$. The interaction was due to the smaller ER in the pure tone condition (M = 1.2%) than in the white noise condition (M = 1.5%) when the cues were presented from the front, whereas when the cues were presented from the rear, the ER was larger in the pure tone condition (M = 1.6%) than in the white noise condition (M = 0.9%). There was also a significant two-way interaction between Spatial Cuing and SOA, $F(2, 46) = 5.293$, $MSE = .001$, $p = .002$, $\eta_p^2 = .187$. Paired sample *t*-tests with Bonferroni correction ($\alpha = .0167$) revealed that the participants made significantly more errors on the uncued trials than on the cued trials at the 100ms SOA, $t(23) = -3.603$, $p = .001$. On the other hand, ERs were

not significantly different between the cued and uncued conditions at the 200ms (p = .578) and 700ms SOAs (p = .108). Importantly, the two-way interaction between Spatial Cuing and SOA in the ER data indicates that the crossmodal spatial cuing effect observed in the RT data analysis reflects the result of a genuine perceptual facilitation, not just some form of a speed-accuracy trade-off (cf. Spence & Driver, 1997a).

3.3.3. Discussion

The results of Experiment 5 once again replicated the crossmodal exogenous spatial cuing effect when the cues were presented from the front (Spence & Driver, 1997a). Compared to the finding of Experiment 4, however, the nature of that cue (i.e., pure tone vs. white noise) had no impact on the pattern of results that was obtained. More importantly, the magnitude of the crossmodal cuing effect was equivalent no matter whether the auditory cues happened to have been presented from in front of, or behind (i.e., outside the visual field of) the participants. Since the rear-to-front crossmodal spatial cuing effect has now been replicated, the phenomenon would seem to be a robust one.

The evidence in support of the existence of rear-to-front crossmodal spatial cuing effects from Experiments 2 and 5 provides a striking contrast from the spatially-specific modulation of crossmodal cuing effects reported previously in the literature (e.g., Driver & Spence, 1998; Schmitt et al., 2001; see also Spence, 2004, for a review). However, it is important to remember that, in Experiments 2 and 5, the participants may simply have confused the perceived location of the auditory cues in the front-back dimension. Note here that both front and rear cues were located approximately 85cm from the participant's head in Experiment 5, with the same azimuth (45°) from the participants' ear positions (thus potentially falling in what is known as the *cone of confusion*, see

Blauert, 1997; Butler, 1986; Makous & Middlebrooks, 1990; Middlebrooks & Green, 1991; see also Footnote 3 in Chapter 1). If the participants in Experiment 5 could not perceive correctly whether the cues were presented from the front or rear, front-back confusions can be a potential explanation for the rear-to-front crossmodal spatial cuing effect. Therefore, a third and last experiment in this chapter was conducted in order to investigate whether the rear-to-front crossmodal spatial cuing effect is attributable to front-back confusion. More specifically, Experiment 6 was designed to investigate the ability of participants to correctly discriminate the location of auditory stimuli.

3.4. Experiment 6

3.4.1. Methods

3.4.1.1. Participants

Twenty-five participants (eleven men and fourteen women) were recruited via the same three sources used in Experiment 5. Twenty-two of whom (ten men and twelve women) had taken part in Experiment 5. The mean of the participants' ages was 25 years, ranging from 17 to 41 years. Twenty-three of the participants were right-handed, one was left-handed, and one was ambidextrous, by self-report. The participants took part in this experiment for approximately 30mins, and were given either two course credits or £5 at the end of the study.

3.4.1.2. Apparatus, materials, design, and procedure

These were identical to those used in Experiment 5, with the exception that the four visual target LEDs were not used in the present study. There were two within-participants factors: Target Position (front vs. rear) and Target Type (pure tone vs. white

noise). The procedure was identical to that used in Experiment 5, with the sole exception that there were no visual targets. Instead, what had been auditory cues in Experiment 5 now became the auditory targets. Auditory targets were presented following the onset of the fixation LED with a random delay of between 400 and 650ms. In Experiment 6, the participants had to respond to the location of the sound (now acting as the auditory target), pressing *7* for the sound from front-left, *9* for the front-right, *1* for the rear-left, or *3* for the rear-right sound. The participants were instructed to use both hands on the numeric keypad on the keyboard, and to respond as rapidly and accurately as possible. They were further instructed to ignore the sound type and to focus on the location of the sound. Importantly, no feedback on their performance was provided during the trials. Each participant completed a total of 144 trials in one block, with 8 possible conditions pseudo-randomly presented a total of 18 times.

3.4.2. Results

All participants responded to more than 95% of the total trials. The average ERs of participants were entered into a box plot, revealing a median of 7.6%, between 1.4% as Q_1 and 16% as Q_3. One participant's average ER across all condition (M = 51.7%) was above the upper limit (M = 37.8%) based on the Tukey's (1977) method, and was therefore removed from the following data analysis. The participants' responses to auditory targets are summarized in Table 3.3.

Table 3.3.

Confusion matrix for the number of responses participants made as a function of auditory target location. Each cell's theoretical maximum is 900. The number of correct responses is shown in bold, and the number of front-back errors is underlined.

Auditory target location	Response			
	Front-left	Front-right	Rear-left	Rear-right
Front-left	**781**	1	114	1
Front-right	0	**850**	0	50
Rear-left	110	2	**784**	0
Rear-right	0	132	0	**767**

A RM-ANOVA with the mean ERs of the within-participants factors of Target Position and Target Type did not yield any significant terms. In order to further investigate whether the participants experienced front-back confusions, the mean front-back ERs from the factor of Target Position were entered into one-sample *t*-tests against .5 (i.e., the hypothetical performance ratio by chance). The analysis revealed that the participants' front-back ERs in response to frontal targets were significantly lower (M = 8.0%) than the chance rate (M = 50%), $t(23) = -20.275$, $p < .001$. When targets were presented from the rear, the participants' front-back ERs (M = 11.6%) were significantly lower than chance levels, $t(23) = -11.573$, $p < .001$. Such results indicate that the participants could correctly discriminate whether the auditory stimuli were presented in the front or rear, at least when they pay attention to do so. Therefore, the results reported in Experiment 6 can be taken to suggest that the rear-to-front crossmodal spatial cuing effect reported in Experiment 5 (and possibly in Experiment 2) was not due to front-back confusions.

3.4.3. Discussion

The results of Experiment 6 demonstrated that the participants were not confused about the front-back locations from which the auditory stimuli were presented. As such, the exogenous crossmodal spatial orienting would seem to lead to a lateralized shift of attention that can be relatively insensitive to the exact co-location of the auditory cues and subsequently presented visual targets, at least when the brief auditory cues fall outside of the visual field (cf. Spence et al., 2004). Before moving on, however, I thought it worthwhile to re-analyse the data from Experiment 5, given the fact that the majority of the participants took part in both Experiments 5 and 6 (i.e., twenty-two out of twenty-five participants). The participants were divided into two groups; specifically, those with higher performance and those with lower performance on the discrimination tasks for the auditory targets in Experiment 6. The data from the three participants who did not take part in Experiment 6 were removed from this analysis. One outlier identified in Experiment 5 was also excluded from the following analysis.

The RT data were divided into two groups based on the median ER in Experiment 6; the High Accuracy group consisted of those participants from Experiment 5 who made <=8% errors in Experiment 6 (N = 13). The Low Accuracy group consisted of the data from those participants who in Experiment 5 made >8% of errors in Experiment 6 (N = 8). The four within-participants factors (Cue Position, Cue Type, Spatial Cuing, & SOA) were then entered into a RM-ANOVA, with the Accuracy group (High vs. Low) as a between-participants factor. Significant interactions were obtained between Spatial Cuing, SOA, and Accuracy, $F(2, 38) = 4.185$, $MSE = 359.577$, $p = .023$, $\eta_p^2 = .181$.

In order to break down the latter three-way interaction, additional RM-ANOVA with the factors of Spatial Cuing and SOA were conducted for the High and Low Accuracy group separately. With the High Accuracy group, there was no significant interaction between

Spatial Cuing and SOA, $F(2, 24) = 2.091$, $MSE = 425.830$, $p = .146$, $\eta_p^2 = .148$, meaning that the crossmodal cuing effect was not modulated by the SOAs. With the Low Accuracy group, by contrast, a significant interaction was found between Spatial Cuing and SOA, $F(2, 14) = 6.157$, $MSE = 246.000$, $p = .012$, $\eta_p^2 = .468$. Paired sample *t*-tests with Bonferroni correction ($\alpha = .0167$) revealed with a significant cuing effect at the 200ms SOA only, $t(7) = -5.308$, $p = .001$ (see Figure 3.4).

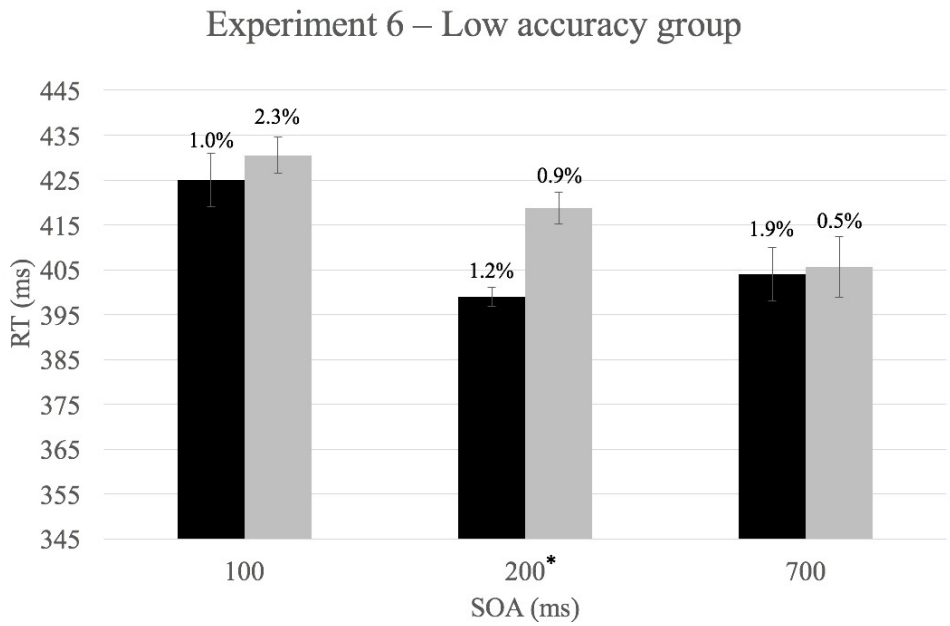


Figure 3.4. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percentages (%) for the Low Accuracy group as a function of cue-target SOA. The black bars represent the mean RTs on those trials in which the cue and target were presented from the same side. The grey bars represent the mean RTs on those trials in which the cue and target were presented from opposite sides. Vertical lines represent standard errors. An asterisk at the 200ms SOA indicates a significant cuing effect based on a paired sample *t*-test from the RT data with Bonferroni correction ($p < .0167$).

The results of the re-analysis of the data from Experiment 5 would appear to suggest that the exogenous crossmodal facilitation effect seems to start as early as the 100ms SOA and to last up to the 700ms SOA for those in the High Accuracy group. The crossmodal facilitation effect for the Low Accuracy group, on the other hand, seems to occur around 200ms after the onset of the auditory cues preceding visual targets on the same side, and

quickly disappears. Taken together, the actual duration and timing of the facilitatory effect for visual targets seem to vary depending on one's ability to discriminate the location of an auditory cue accurately. Furthermore, the facilitation effect may occur sooner and last longer for those participants who exhibited higher discrimination accuracy, as compared to those with low discrimination accuracy. What is more interesting, though, is the fact that rear-to-front crossmodal spatial cuing effects were documented regardless of whether the participants were in the High or Low Accuracy group. Therefore, the results of this re-analysis of the data from Experiment 5 add weight to the conclusion that, unlike the conventional belief (Spence, 2004; Spence et al., 2004), the exact co-location of the auditory cue and the visual target is not always vital when it comes to eliciting a significant crossmodal spatial cuing effect, at least not when the brief cue precedes the target on the same *lateral position, and outside the visual field*; the attentional shift elicited by the presentation of a spatially-uninformative auditory cue, either at front or rear, will facilitate visual information processing speed for the frontal visual target presented on the same side.

3.5. General discussion

The results of the three experiments reported in the present chapter support a number of important conclusions concerning the crossmodal orienting of spatial attention (see Van der Stoep, Spence, Nijboer, & Van der Stigchel, 2015b, for a review). First, the presentation of an auditory cue can induce a robust crossmodal exogenous cuing effect, even if the auditory cue is entirely task-irrelevant. Second, crossmodal exogenous spatial cuing effects can often last over 300ms from the onset of an auditory cue, potentially depending on the sound localisation capability of the participants. More importantly, the results reported in this chapter confirmed that the auditory cues from very *different*

spatial locations on the same side of space can still facilitate the perception of the elevation of the frontal visual targets. According to the results of Experiments 2 and 5, all that seems to matter is that the cues and targets are presented from the same *side* (i.e., left or right).

The evidence demonstrating the rear-to-front crossmodal spatial cuing effect 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 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 (Chapter 1; see Spence et al., 2004, for a review). But how should such an unexpected cuing effect be explained? An analysis of the response properties of audiovisual (multisensory) neurons in the SC might help to provide an answer here. Indeed, the role of the spatial co-location of the cue and target stimuli in the crossmodal cuing effect has often been explained in terms of the response properties of the multisensory neurons in the SC (Chapter 1; e.g., Spence, 2013; Spence & Driver, 1997a, 1999; see also Chapter 4).

In the animal model (i.e., typically 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, Vaughan, Wallace, & Stein, 2001). In the rostral SC, visual RFs have been documented to 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 Figure 3.5 for a schematic

suggestion along these lines; see also Kadunce et al., 1997; Meredith & Stein, 1996; Wallace et al., 1996). As such, an auditory cue presented in the rear-left position in Experiment 5 (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.[14]

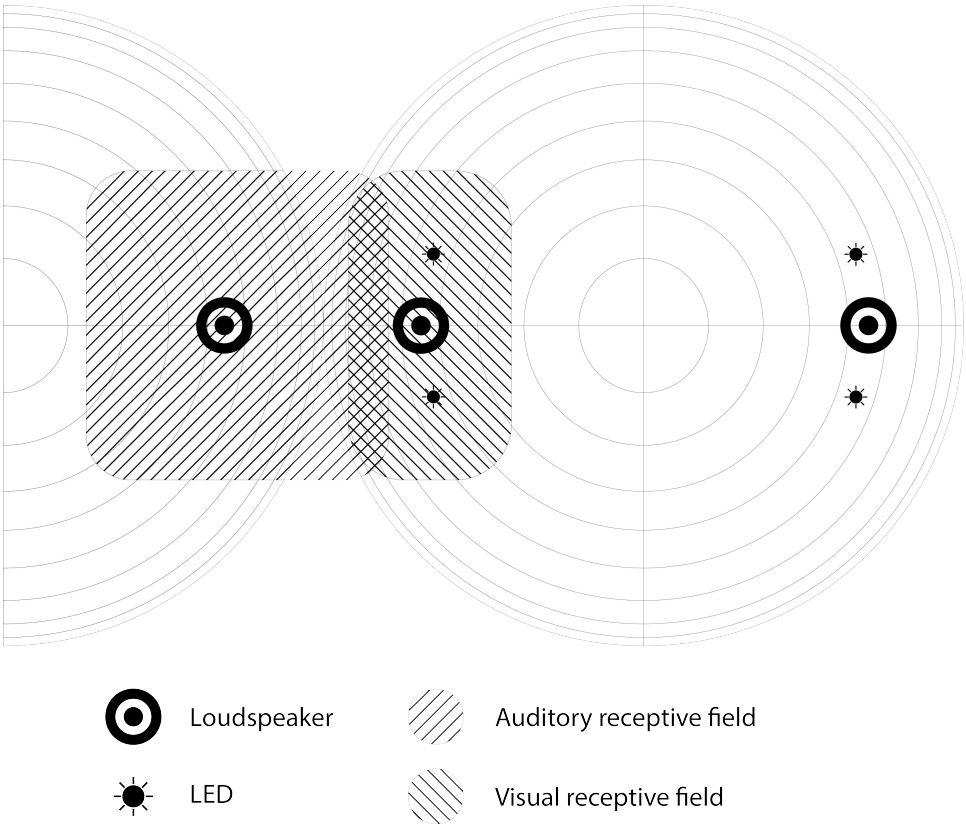


Figure 3.5. A schematic illustration of the spatial extent of the auditory and visual receptive fields (RFs) of a single neuron in the superior colliculus. The illustration is modelled on Meredith and Stein (1996). Frontal audiovisual space is represented by the full circle on the right, and posterior auditory space by the crescent on the left. The horizontal and vertical lines represent an azimuth of 0° and an elevation of 0°, respectively. Each concentric circle represents 10° of space. The figure illustrates how a multisensory neuron may have an auditory RF that extends well into rear space, while maintaining a visual RF in frontal space.

[14] The neurophysiological data, based primarily on anaesthetised cats, can only provide a hypothetical explanation of the rear-to-front crossmodal spatial cuing effects observed from awake human participants. However, that said, similar properties, such as RF alignment and multisensory integration, have also been reported in the monkey SC (see Wallace et al., 1996). Therefore, the neurophysiological perspective provides a viable account for the rear-to-front crossmodal spatial cuing effect reported in Experiments 2 and 5.

The results of the experiments reported in the present chapter demonstrate for the second time that the relative location of the auditory cues and visual targets does not always matter, particularly when brief cues (100ms or less) are presented outside of the current field-of-view. Here, equivalent cuing effects were elicited by both rear and frontal auditory cues prior to the presentation of frontal visual targets. The findings reported in this chapter suggest that presenting a short alarm sound at the back of a driver's head might not direct his/her attention to the rear, as perhaps intended, even though the driver would be able to localise the sound correctly.

Chapter 4. On the spatial specificity of audiovisual cuing effects

4.1. Introduction

The experiments reported in Chapters 2 and 3 demonstrated that the presentation of a task-irrelevant auditory cue can facilitate the perception of a visual target presented on the same rather than opposite side (between-hemifield spatial cuing effect; see Chapter 1). More importantly, the results of Experiment 5 replicated the rear-to-front crossmodal spatial cuing effect first reported in Experiment 2. The front-back confusion was ruled out as a potential explanation for the rear-to-front crossmodal spatial cuing effect (see Experiment 6 in Chapter 3). The findings reported in Chapters 2 and 3 therefore suggest that the magnitude of a crossmodal spatial cuing effect is the same regardless of whether or not the cue and target are co-located within the same (left or right) hemifield. Such a conclusion, if correct, would contradict previous reports concerning the spatial specificity of exogenous crossmodal cuing (Driver & Spence, 1998; Schmitt et al., 2001; see also Spence & McDonald, 2004; Spence et al., 2004, for reviews). However, when I started looking for experimental data from the published literature in support of the within-hemifield spatial cuing effect, I noticed that the latter phenomenon had not been studied anything like as thoroughly as the between-hemifield spatial cuing effect. This led to the question of whether exogenous crossmodal cuing effects really are as spatially-specific as some researchers have led us to believe?

To date, many authors have argued that exogenous crossmodal cuing effects are spatially-specific (Driver & Spence, 1998; Schmitt et al., 2001; see Spence et al., 2004,

for a review). The claim is that the presentation of a spatially-nonpredictive cue in one sensory modality will direct a participant's attention to a specific location (or region of space, depending on the paradigm used) rather than to the entire hemifield in which the cue happens to have been presented (i.e., the left or right side of space; Spence et al., 2004). For instance, Schmitt et al. investigated whether changing the cue-target distance would modulate the magnitude of crossmodal spatial cuing effects. More specifically, they assessed distance effects using four different combinations of cue and target stimuli: visual-visual, visual-auditory, auditory-visual, and auditory-auditory. There were a total of four cue-target distance conditions in the study: 0-distance if the cue and target were presented from the same location; 1-distance if the cue and target were presented next to each other; 2-distance if there was an unused cue location between the presented stimuli; and 3-distance if the cue and target were presented from the outer-left and outer-right positions, or vice versa.

In Schmitt et al.'s (2001) study, an LED was placed at the centre of each of four loudspeakers. The stimuli were presented 10° or 20° to either side of central fixation (inner and outer eccentricities, respectively). All of the stimuli were presented at a fixed distance from the participants (i.e., on a circle centred on the participant's head; see Figure 4.1a). On each trial, a target was presented after a variable SOA (125, 175, 300, 575, or 825ms), following the onset of the cue. The participants had to press one of the four laterally-placed response keys (e.g., an outer-left key for the outer-left target, an inner-right key for the inner-right target, etc.) to indicate the perceived location of the target as rapidly and accurately as possible.

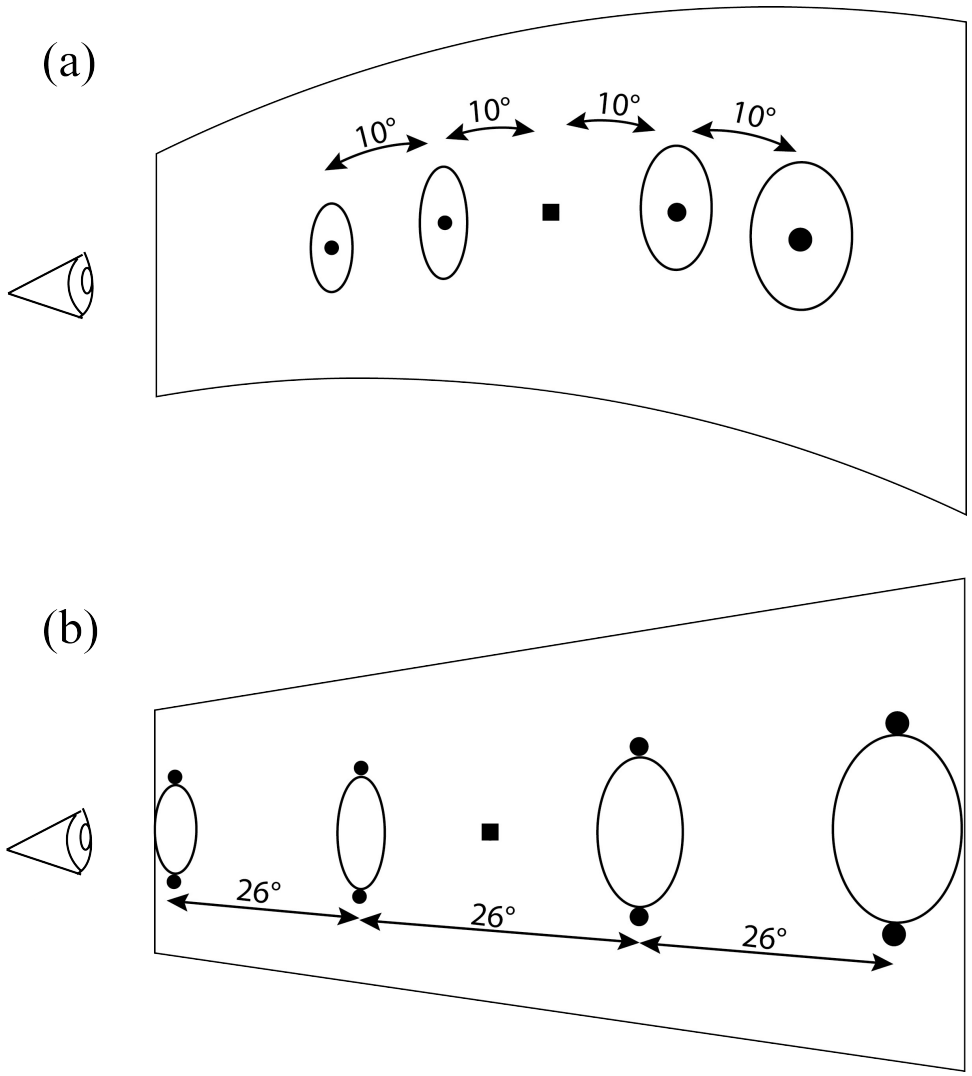


Figure 4.1. (a) Schematic illustrations of Schmitt et al.'s (2001) experimental set-up and (b) the set-up from Driver and Spence's (1998) orthogonal spatial cuing paradigm. The four loudspeakers used to present the auditory cues are shown as ellipses. Target LEDs are represented as black dots (a) in front of the loudspeakers or (b) above and below each loudspeaker. The fixation LED (shown here as a black square) was placed between the inner loudspeakers in both studies.

Schmitt et al. (2001) reported that RTs were shortest when the visual targets were preceded by either visual or auditory cues from the same position (i.e., 0-distance condition) rather than from a different location (at all SOAs [125, 175, 300, 575, & 825ms]). Furthermore, RTs in the 1-distance condition were faster than those in the 2-distance condition, which, in turn, were faster than those in the 3-distance condition. These results were therefore taken to support the existence of a so-called distance effect.

These findings add further support to the gradient model of spatial attention, according to which attentional facilitation is greatest at the cued location and decreases as a function of the distance from the cued location (e.g., Downing, 1988; Downing & Pinker, 1985; Mangun & Hillyard, 1988; Shulman, Wilson, & Sheehy, 1985, for visual gradients; Mock, Seay, Charney, Holmes, & Golob, 2015; Mondor & Zatorre, 1995; Teder-Sälejärvi & Hillyard, 1998, for auditory gradients; see also Kennett & Driver, 2014, for a discussion in the context of visuotactile cuing). However, there are two possible explanations for the slower RTs in the 1- than the 0-distance condition. One is the within-hemifield spatial cuing effect; The other is that the distance effect between the 0- and the 1-distance might simply reflect a standard between-hemifield spatial cuing effect when the auditory cues and visual targets just so happened to have been presented from the inner two locations (e.g., Spence & Driver, 1997a). Therefore, in-and-of-themselves, distance effects such as these cannot be taken as evidence that the presentation of a task-irrelevant auditory cue can shift visual attention in a spatially-specific manner within the cued hemifield.

Furthermore, it is important to note that the distance effects reported by Schmitt et al. (2001) were potentially confounded by response priming. Specifically, the dimension along which the auditory cues varied was the same as that of participants' responding. Some years ago, Spence and Driver (1994, 1997a) pointed out that in certain non-orthogonal spatial discrimination tasks, faster RTs on cued than on uncued trials might simply reflect response priming rather than attentional facilitation. One popular method in order to avoid response priming confound in the majority of spatial cuing studies that have been published to date is the orthogonal spatial cuing paradigm (e.g., Ho et al., 2006; Spence & Driver, 1994, 1996, 1997a). In those studies that have used such an approach, the dimension along which the cue varies (e.g., left or right side) is

intentionally made *orthogonal* to that of responses (e.g., discriminating upper vs. lower target locations). One key aim of the orthogonal cuing paradigm is to try and isolate any crossmodal attention facilitation from the possible confounding effects that might otherwise be attributable to response priming (see Footnote 2 in Chapter 1; Spence & McDonald, 2004).

In fact, to date, no studies have investigated within-hemifield exogenous audiovisual spatial cuing effects without potential response bias concerns, except for a single study (Driver & Spence, 1998) described briefly in Spence et al. (2004) and Spence and McDonald (2004). In particular, these researchers reported an experiment in which the spatial specificity of audiovisual crossmodal cuing effects were assessed using the orthogonal cuing paradigm. In this case, the experimental set-up included two cue loudspeakers on each side with a pair of target LEDs, one placed above and the other below each loudspeaker (see Figure 4.1b). On each trial, the participants had to make a speeded elevation discrimination response (i.e., upper vs. lower) to the visual target presented from one of the eight possible locations, while ignoring a spatially-nonpredictive auditory cue presented shortly beforehand. Spence et al. reported that "the presentation of an auditory cue […] led to a spatially specific shift of attention that facilitated visual elevation discrimination response latencies maximally for visual targets presented from directly above and below the auditory cued location" (p. 9). Importantly, such within-hemifield spatial cuing effects were reported from all four of the possible cue positions (see Figure 4.2). RTs were 20-40ms faster when the cue and target were presented from the same position than when they were presented from different lateral positions within the cued hemifield. Furthermore, RTs to visual targets tended to increase as a function of the increasing cue-target distance, thus providing further support for the gradient model of spatial attention (e.g., Downing & Pinker, 1985) and

distance effects (e.g., Schmitt et al., 2001). It is, however, worth noting that these experimental findings have only ever been reported in review papers (e.g., Spence et al., 2004). As a result, the data supporting the spatial specificity of the audiovisual cuing effect has never been made available for closer inspection.

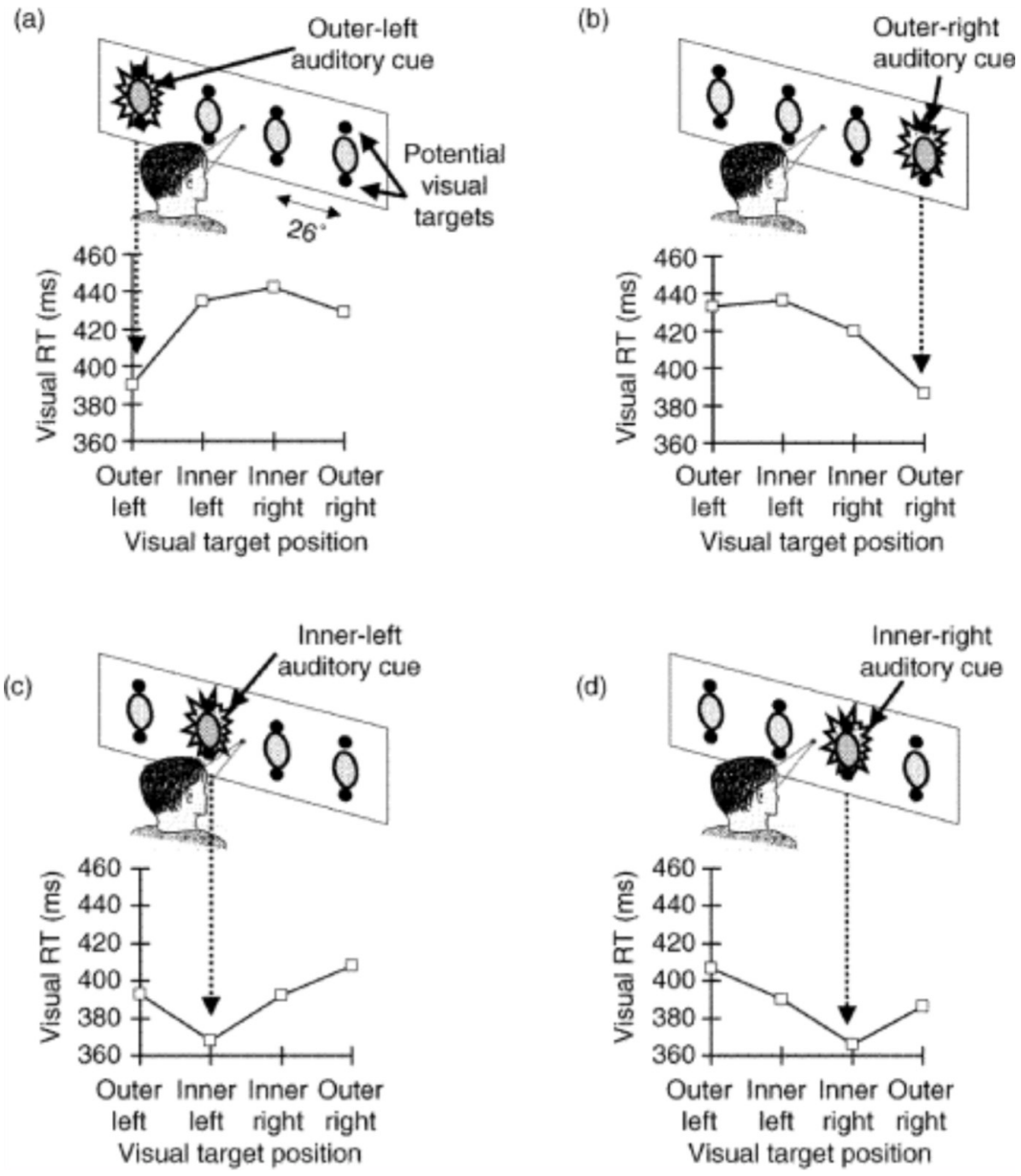


Figure 4.2. Mean reaction times (RTs) in milliseconds (ms) in the (a) outer-left, (b) outer-right, (c) inner-left, and (d) inner-right auditory cue conditions as a function of the visual target positions (reprinted with permission from Spence et al., 2004, p. 286).

In summary, the evidence that has been published to date indicates that localised auditory cues can exogenously orient attention to the cued hemifield (e.g., Spence & Driver, 1997a). Furthermore, audiovisual spatial cuing effects have been reported to be larger when the cue and target are presented from the same, rather than from different lateral positions within the cued hemifield (see Driver & Spence, 1998; also see Spence et al., 2004). However, to date, only limited evidence has been provided in support of the existence of within-hemifield audiovisual spatial cuing effects. Furthermore, to the best of my knowledge, there has been no audiotactile or visuotactile cuing study on within-hemifield spatial cuing effects (though see Kennett & Driver, 2014[15]).

Therefore, in order to better understand the spatial specificity of audiovisual exogenous cuing effects (which might be important in both an applied and theoretical context; e.g., see Baldwin, Spence, Bliss, Brill, Wogalter, Mayhorn, & Ferris, 2012; Ho & Spence, 2008, for reviews), three experiments were designed to investigate within-hemifield spatial cuing and between-hemifield spatial cuing. The experimental set-up was closely modelled on that reported almost two decades ago by Driver and Spence (1998; i.e., two possible auditory cue positions on each side, and two possible visual target locations; one directly above and another directly below each loudspeaker; see Figure 4.3). Because the spatial resolution in vision is known to be better at the fovea than in the periphery (DeValois & DeValois, 1991; see also Carrasco & Frieder, 1997), the eccentricity of visual targets might affect participants' target response latencies (e.g., Carrasco et al., 1995; Wolfe et al., 1998; see also the later discussion). In order to ensure the spatial

[15] Kennett and Driver's (2014) study investigated how the within-hemifield alignment between hand postures (cue locations) and visual targets influenced between-hemifield exogenous spatial cuing effects. The cuing effects for the outer visual targets were larger when the participant's hands were aligned with those targets than when they were misaligned. However, cue-target alignment did not influence the spatial cuing effects for the inner visual targets. That is, RTs were faster when the cue and target stimuli were presented ipsilaterally than when they were presented contralaterally, regardless of the cue-target alignment. That said, their study did not investigate whether RTs on cued trials were any faster than when the cue and targets stimuli were presented within the same hemifield but from different locations.

specificity of crossmodal cuing effects are not limited to a certain eccentricity, the three experiments reported here used different eccentricities of auditory cues and visual targets. The loudspeakers were evenly separated laterally by 30° in Experiments 7 and 8, and by 10° in Experiment 9. The loudspeakers and LEDs were vertically separated by approximately 35° in Experiment 7, by 19° in Experiment 8, and by 4° in Experiment 9 (see Figure 4.3).

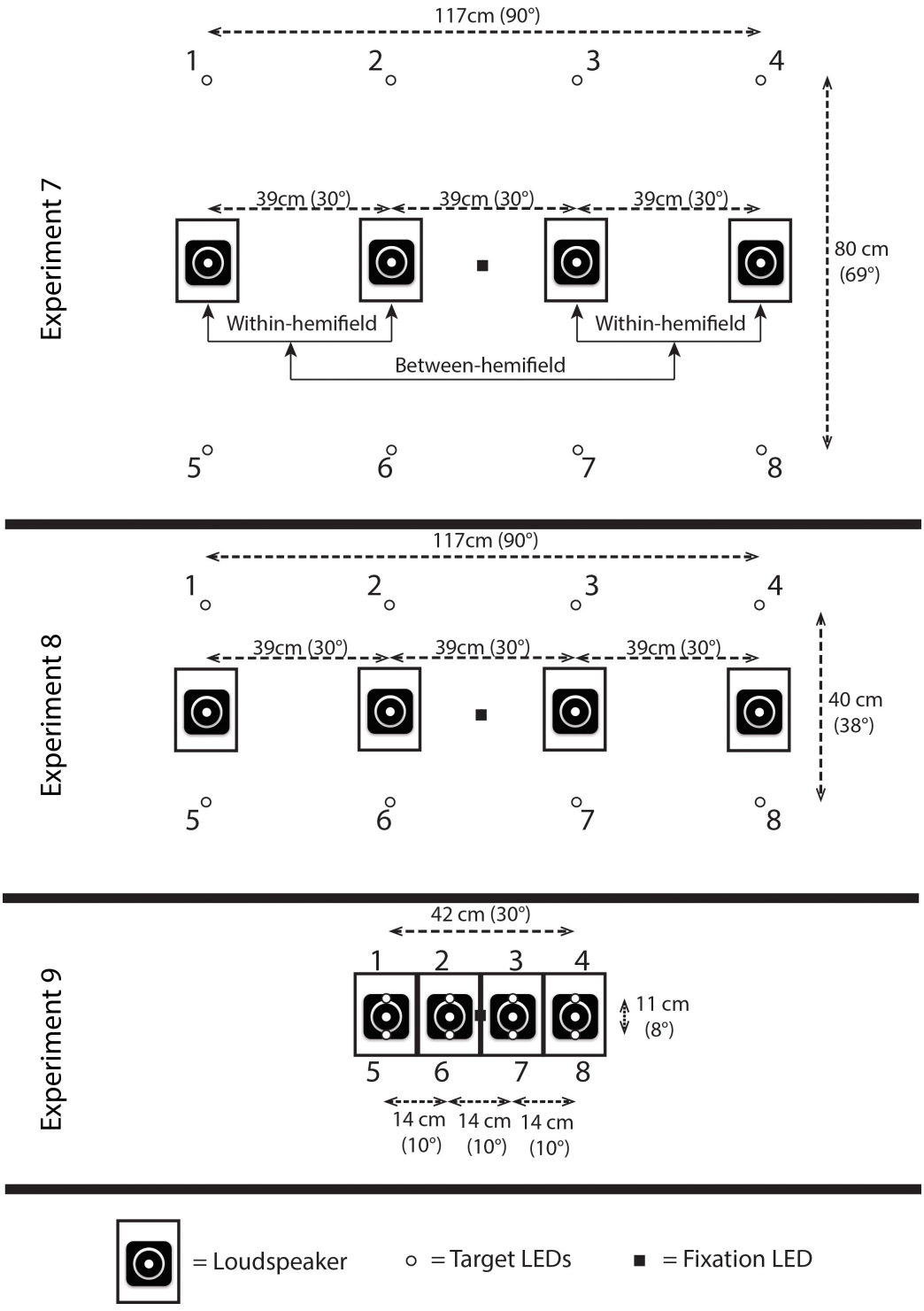


Figure 4.3. Schematic views of the positions of the loudspeakers and visual targets (1-8) in Experiments 7, 8, and 9 from the point of view of the participant. Within- and between-hemifield spatial cuing conditions are illustrated for Experiment 7 only.

If crossmodal exogenous spatial cuing effects are indeed spatially-specific, then (1) the presentation of a spatially-uninformative auditory cue would elicit faster RTs to visual targets presented from the same position as compared to those from a different lateral position within the cued hemifield (see Driver & Spence, 1998; Figure 4.2). In other words, within-hemifield spatial cuing effects should be observed. Furthermore, (2) RTs ought to be faster when the cue and target are presented from the same rather than different sides regardless of the cue and target eccentricity. In other words, between-hemifield spatial cuing effects should be observed (e.g., Spence & Driver, 1997a).

4.2. Experiment 7

4.2.1. Methods

4.2.1.1. Participants

Twenty-two participants (nine male and thirteen female) volunteered to take part in this study through the OPR and the RPS. Their average age was 22 years, ranging from 18 to 33 years of age. The participants had normal (or corrected-to-normal) vision and hearing, and all were right-handed except three left-handers, by self-report. The experiment lasted for approximately 30 minutes. The participants were given either two course credits or else were paid £5 in return for taking part in the study.

4.2.1.2 Apparatus and materials

Experiment 7 as well as other two experiments reported in this chapter were conducted in a darkened room (320 x 144 x 220cm), using MATLAB R2014a with PSYCHTOOLBOX 3.0.12 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Four loudspeakers (Ricco 2.0 Channel Wooden Speaker Home Hifi System, model number:

T2018) were situated in front of the participant's eye-level (see Figure 4.3). The centres of the loudspeaker cones at the outer-left and the outer-right positions were separated by 117cm, and the centre of each loudspeaker was separated from its nearest neighbour(s) by 39cm, evenly separated laterally by 30° seen from the participant's location between neighbouring loudspeakers. Each loudspeaker was equipped with a 3.5-inch diameter single-cone, capable of producing frequencies between 80Hz and 20kHz. Broadband noise was used as the auditory cue, matched at 72dBA between all four loudspeakers from the participant's head position. All loudspeakers were connected to the same USB audio interface used in Experiments 1-6. A pair of red target LEDs (identical to those used in Experiments 4-6) was placed above and below each loudspeaker cone. The target LEDs were installed 40cm either above or below the centre of the loudspeaker cone, giving rise to approximately 69° of vertical visual angle between the upper and lower targets from the location of the participant.

The four loudspeakers were placed on a wooden shelf, 117cm above the ground (as measured from the centre of the loudspeaker cones) to approximately match the participant's eye-level. One red LED (identical to the target LEDs) was placed 58.5cm in front of the participant at eye-level, 117cm above the ground, between the two inner loudspeakers, as a fixation point. The same computer monitor used in Experiments 4-6 was placed below the frontal loudspeaker shelf in order to provide instructions. The participant was seated approximately 58.5cm from the red fixation LED.

4.2.1.3. Design

There were two within-participants factors: Cue Location (outer-left, inner-left, inner-right, or outer-right) and Target Location (outer-left, inner-left, inner-right, or outer-right). Crossing these factors yielded 16 possible conditions, with each condition

presented pseudo-randomly 6 times within a block of trials. There were three blocks of trials, with the participants having the opportunity to take a short break after each block of trials.

4.2.1.4. Procedure

Each trial started with the illumination of the fixation LED, followed by a random delay of between 400 and 650ms. Then, a task-irrelevant auditory cue was presented from one of the four loudspeakers for 100ms. After a random delay of 100-200ms (SOA), a visual target was presented from one of the eight possible locations for 140ms (see Figure 4.3). The duration of any random delay on each trial was selected from the discrete uniform distribution. In order to indicate the elevation of the target LED, the participants had to press either the *up* or *down* arrow key on a computer keyboard placed on their lap, regardless of the lateral position from which the target was presented. The participants were instructed to ignore the auditory cues, and to respond as rapidly and accurately as possible to the visual targets. When the participant's response had been registered, or else when 2,000ms had elapsed after the onset of the visual target, the fixation LED was extinguished and the next trial was initiated. The instructions were displayed on the computer screen placed under the wooden shelf. Following the instructions, the participants completed ten practice trials, while the experimenter remained in the experiment room. After the practice trials, I asked if the participants had any questions. Once their questions had been answered and they confirmed that they had no further questions, I exited the experiment room and closed the door, before the actual trial began.

4.2.2. Results

All of the participants responded on over 95% of the trials. A box-plot of the participants' average RTs revealed a median of 390ms, with 362ms as Q_1 and 438ms as Q_3. Another box-plot of the participants average ERs revealed a median of 0%, with 0% as Q_1 and 1.1% as Q_3. One participant's average RT (M = 554ms) was greater than the upper limit (M = 553ms) based on the Tukey's (1977) method, and was therefore excluded from the data analysis. Two participants' average ERs (Ms = 3.1% and 6.3%) were above the upper limit (M = 2.6%), and were also removed from the data analysis. Any trial data including incorrect responses, responses immediately following an incorrect response, and RTs outside of the range between 150 and 1,500ms were removed from the data analysis (see Chapters 2 and 3, for similar exclusion criteria). A total of 141 trials (2.6%) were removed based on these exclusion criteria.

RT data analysis

For comparison with Figure 4.2, the mean RTs in response to visual targets following the presentation of an auditory cue either from the outer-left, outer-right, inner-left, or inner-right position are summarised in Figure 4.4. The two within-participants factors of Cue Location and Target Location were entered into a RM-ANOVA. The analysis revealed a significant main effect of Target Location, $F(3, 54) = 11.546$, $MSE = 808.362$, $p < .001$, $\eta_p^2 = .391$. The participants responded significantly more rapidly to the inner-left targets (M = 400ms) than to the outer-left targets (M = 415ms), $t(18) = 2.907$, $p = .009$. Similarly, RTs to the inner-right targets (M = 391ms) were significantly faster than those to the outer-right targets (M = 412ms), $t(18) = -6.866$, $p < .001$. The significant interaction between Cue and Target Location, $F(9, 162) = 7.908$, $MSE = 453.845$, $p < .001$, $\eta_p^2 = .305$, highlights the presence of a significant crossmodal spatial cuing effect.

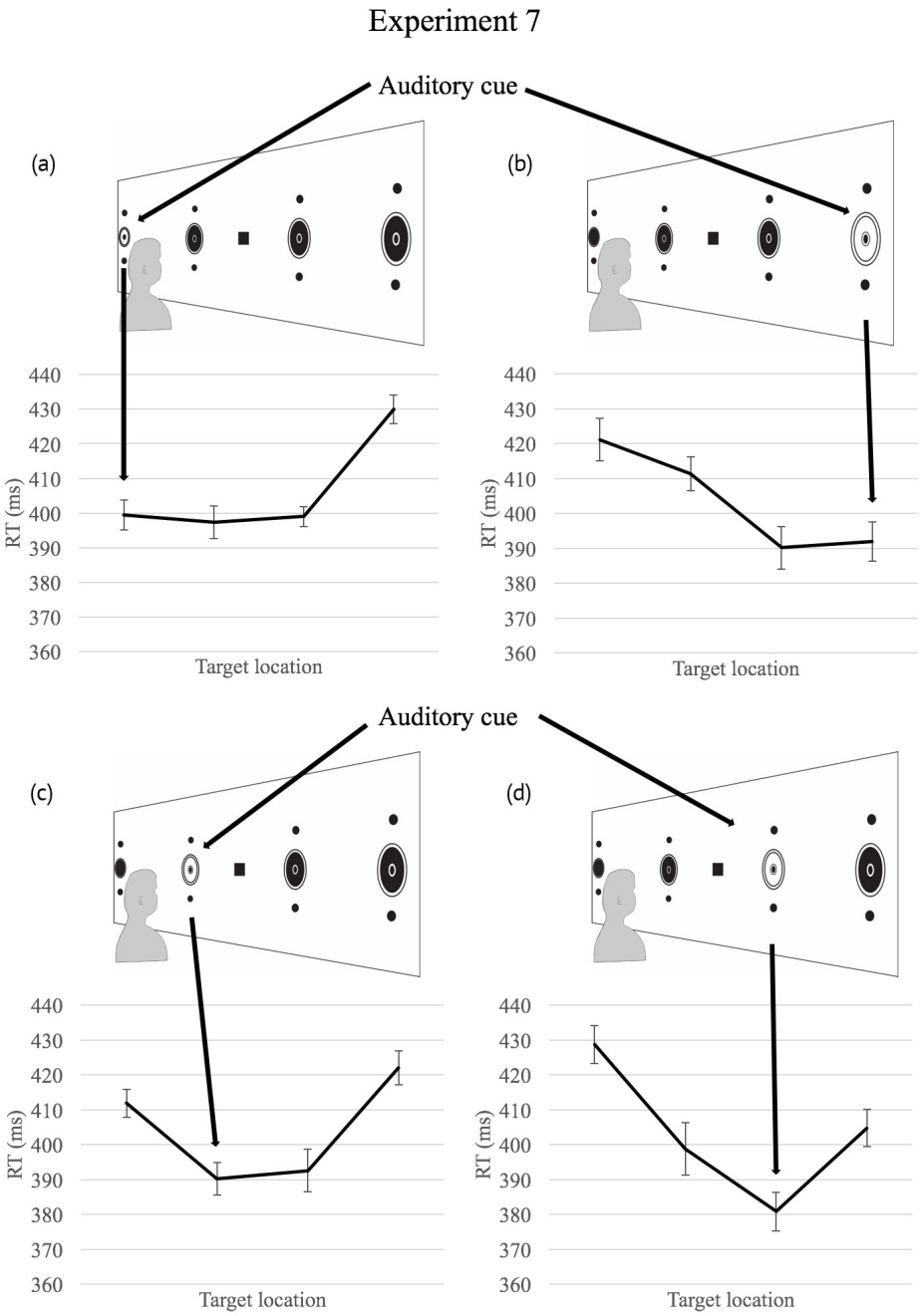


Figure 4.4. Mean reaction times (RTs) in milliseconds (ms) in the (a) outer-left, (b) outer-right, (c) inner-left, and (d) inner-right auditory cue conditions as a function of the Target Location in Experiment 7. The black dots and square represent the possible visual target locations and the fixation LED, respectively. The ellipses represent the loudspeakers, and the bright ellipse represents the location of the auditory cue. Standard errors of RTs are indicated by the vertical lines.

Two planned paired sample *t*-tests were conducted at each eccentricity with the RT data from those trials in which the cue and target were presented from the same hemifield. The analysis revealed that when the auditory cues were presented from the inner eccentricity, RTs were significantly faster when the visual targets were presented from the same position (M = 386ms) than from a different lateral position within the cued hemifield (M = 409ms), $t(18) = -6.105$, $p < .001$. When the cues were presented from the outer eccentricity, however, RTs to targets presented from the same position within the cued hemifield (M = 395ms) were not statistically different compared to those presented from a different lateral position within the cued hemifield (M = 394ms), $t(18) = .228$, $p = .822$. In summary, significant within-hemifield spatial cuing effects were documented only on those trials in which the auditory cues had been presented from the inner eccentricity (at an eccentricity of 15°; see Figure 4.5).

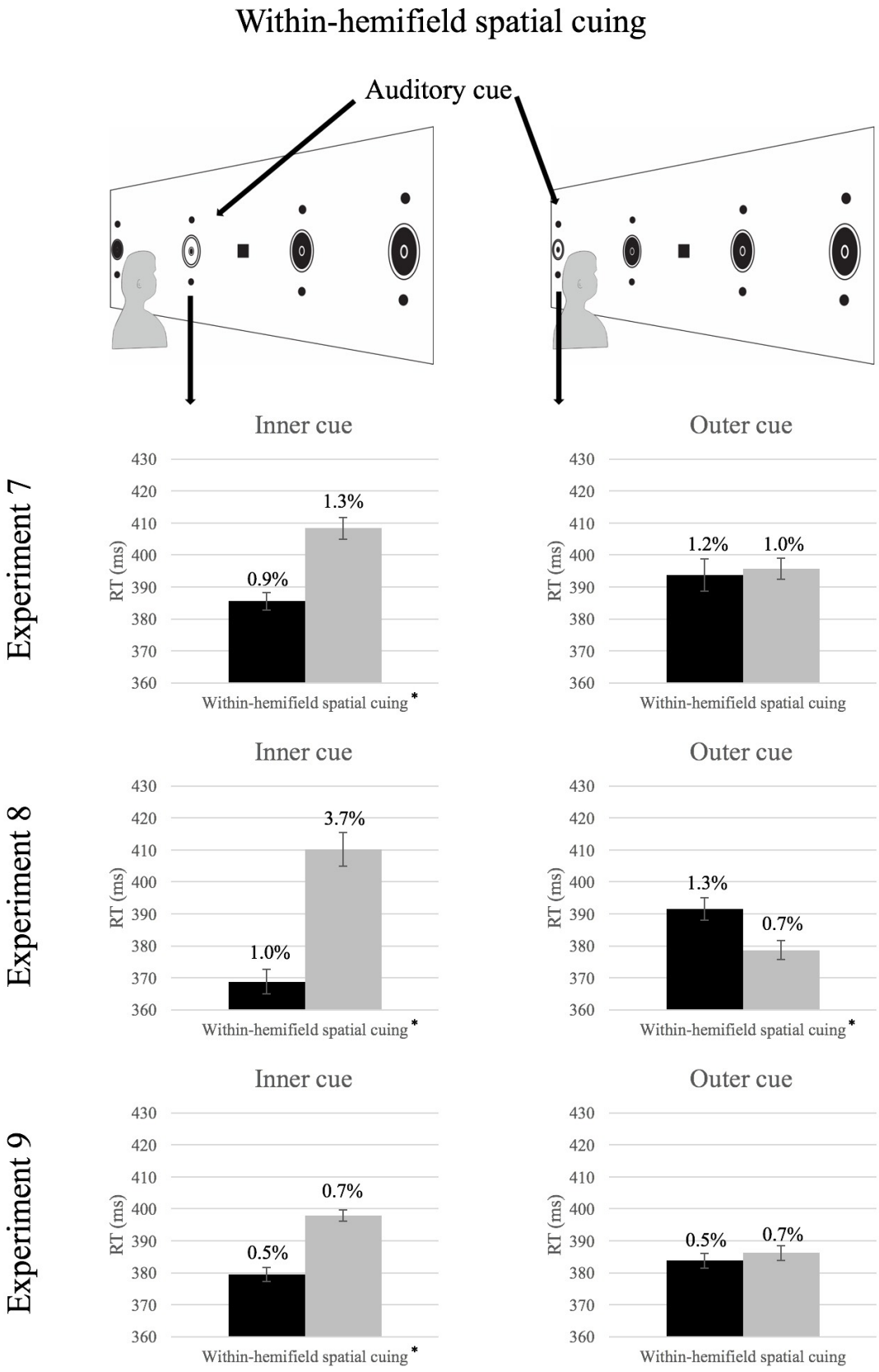


Figure 4.5. Mean reaction times (RTs) in milliseconds (ms) and mean error rates (%) as a function of within-hemifield spatial cuing for Experiments 7, 8, and 9. Black bars represent the mean RT on trials in which the cue and target were presented from the

same position. Grey bars represent the mean RT on trials in which the cue and target were presented from different lateral locations within the cued hemifield. The left column represents the mean RT on those trials in which the auditory cues were presented from the inner eccentricity regardless of the hemifield (left or right). The right column represents the mean RT on trials in which the cues were presented from the outer eccentricity regardless of the hemifield. Standard errors of mean RTs are indicated by the vertical lines. Asterisks are used to indicate significant RT difference between the within-hemifield spatial cuing conditions ($\alpha = .05$).

A RM-ANOVA with the within-participants factor of Between-hemifield Spatial Cuing (cued if the cue and target were presented from the same side vs. uncued if not) was conducted in order to investigate whether there was a between-hemifield spatial cuing effect. The analysis revealed a significant main effect of Between-hemifield Spatial Cuing, $F(1, 18) = 43.069$, $MSE = 62.073$, $p < .001$, $\eta_p^2 = .705$, with participants responding more rapidly to targets when the cue was presented from the same (M = 396ms) rather than the opposite (M = 413ms) side (see Figure 4.6).

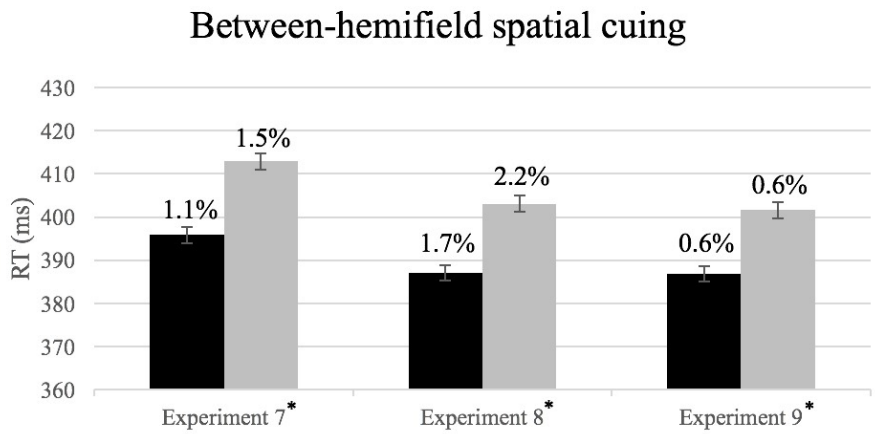


Figure 4.6. Mean reaction times (RTs) in milliseconds (ms) and mean error rates in percentages (%) as a function of between-hemifield spatial cuing for Experiments 7, 8, and 9. Black bars represent the mean RTs on those trials in which the cue and target were presented in the same hemifield. Grey bars represent the mean RTs on those trials in which the cue and target were presented from different hemifields. Standard errors of mean RTs are indicated by the vertical lines. Asterisks are used to indicate significant between-hemifield spatial cuing effects ($\alpha = .05$).

ER data analysis

A RM-ANOVA with the two within-participants factors of Cue and Target Location revealed no significant terms.

4.2.3. Discussion

The results of Experiment 7 confirmed the existence of the standard between-hemifield spatial cuing effect (e.g., Spence & Driver, 1997a). More importantly, the within-hemifield spatial cuing effect was only documented when the auditory cues were presented from the inner eccentricity, thus contrasting with the conventional view concerning the spatial specificity of exogenous crossmodal cuing effects (e.g., Driver & Spence, 1998). Furthermore, based on the lack of any significant main effects or interactions in the error data, the documented spatial cuing effects would appear to reflect a genuine attentional facilitation rather than any kind of speed-accuracy trade-off (see Duncan, 1980; Spence, Pavani, & Driver, 2000).

The lack of within-hemifield spatial cuing effects following the presentation of the auditory cues from the outer eccentricity could presumably be attributable to the confounding influence of *eccentricity* on participants' visual target discrimination performance (e.g., Carrasco et al., 1995; Wolfe et al., 1998). It should be noted that those visual stimuli that are presented from, or near to, fixation tend to be detected more rapidly (and accurately) than those that are presented from further away. In Experiment 7, the inner and outer eccentricities were separated laterally by 30°. Consequently, the inner targets should have been responded to more rapidly than the outer targets, as confirmed here, regardless of the location of the auditory cue (see Carrasco et al., 1995; Wolfe et al., 1998). Therefore, any crossmodal facilitation effects for the outer targets following the presentation of an auditory cue at the same lateral position might have not

been detected due to the slower baseline RTs to outer targets than to inner targets. Consequently, the confirmed within-hemifield spatial cuing effect following the presentation of the auditory cues from the inner eccentricity can also be explained by the interaction between the eccentricity effect and the between-hemifield spatial cuing effect.

Generally-speaking, the more eccentric the visual stimuli, the more pronounced the eccentricity effect becomes (Carrasco et al., 1995; see also Carrasco & Frieder, 1997). In an attempt to reduce the influence of this effect in the next experiment, the visual targets were placed 20cm above and below each loudspeaker, instead of 40cm as had been the case in Experiment 7. The reduced vertical cue-target separation was expected to increase the chance to detect within-hemifield spatial cuing effect in the RT data analysis, particularly when the auditory cues were presented from the outer eccentricity (at an eccentricity of 45°; see Figure 4.3).

4.3. Experiment 8

4.3.1. Methods

4.3.1.1. Participants

Twenty-four participants (six male and eighteen female) volunteered to take part in this experiment through the OPR. Their average age was 27 years, ranging from 18 to 51 years. All of the participants reported normal or normal-to-corrected vision, and normal hearing. They were all right-handed except one left-hander based on self-report. Experiment 8 took approximately 30 minutes to complete. Each participant was paid £5 at the end of the study.

4.3.1.2. Apparatus, materials, design, and procedure

These were the same as in Experiment 7, except that the visual targets were placed 20cm above and below each loudspeaker. The placement of the visual targets gave rise to a 39° vertical visual angle between the upper and lower targets from the participant's point of view.

4.3.2. Results

All of the participants responded to over 95% of the total trials. A box-plot of the participants' average RTs revealed a median of 376ms, with 341ms as Q_1 and 441ms as Q_3. Another box-plot of the participants' average ERs revealed a median of 1.4%, with 0.7% as Q_1 and 2.8% as Q_3. Two participants' mean ERs (Ms = 9.7% and 50%) were above the upper limit (M = 5.9%) based on the Tukey's (1977) method, and were therefore removed from the data analysis. A total of 199 trials (3.1%) were removed based on the exclusion criteria used in Experiment 7.

RT data analysis

For comparison with Figure 4.2, the mean RTs in response to visual targets following the presentation of an auditory cue either from the outer-left, outer-right, inner-left, or inner-right position are summarised in Figure 4.7. The two within-participants factors of Cue Location and Target Location were entered into a RM-ANOVA. The analysis revealed a significant main effect of Target Location, $F(3, 63) = 23.304$, $MSE = 958.679$, $p < .001$, $\eta_p^2 = .526$. The participants responded significantly more rapidly to the inner-left targets (M = 386ms) than to the outer-left targets (M = 412ms), $t(21) = 5.653$, $p < .001$. Similarly, RTs to the inner-right targets (M = 379ms) were significantly faster than those to the outer-right targets (M = 406ms), $t(21) = -5.463$, $p < .001$. The significant

interaction between Cue and Target Location, $F(9, 189) = 9.310$, $MSE = 486.643$, $p < .001$, $\eta_p^2 = .307$, highlights the presence of a significant crossmodal spatial cuing effect.

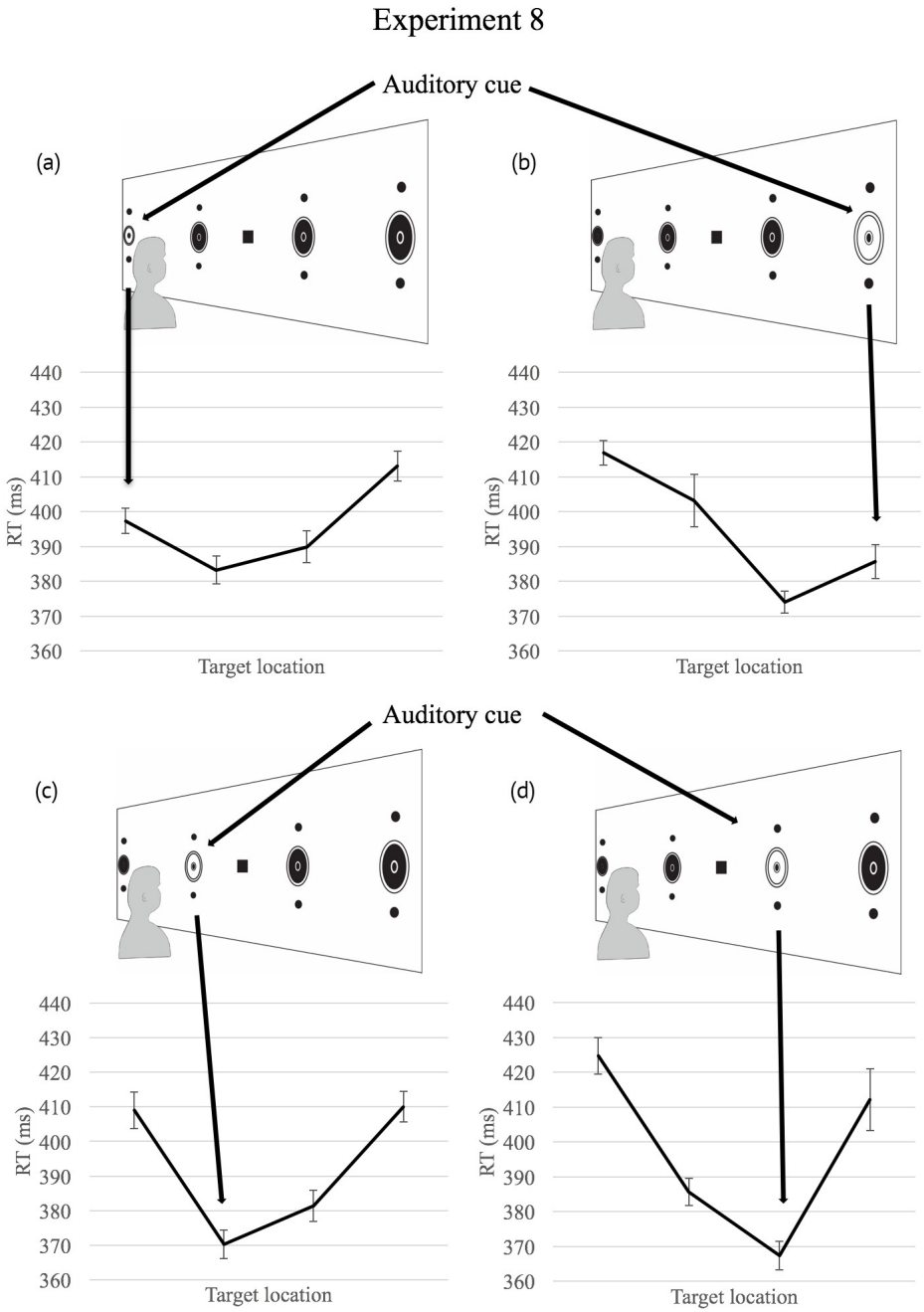


Figure 4.7. Mean reaction times (RTs) in milliseconds (ms) in the (a) outer-left, (b) outer-right, (c) inner-left, and (d) inner-right auditory cue conditions as a function of the Target Location in Experiment 8. The black dots and square represent the possible visual target locations and the fixation LED, respectively. The ellipses represent the loudspeakers, and the bright ellipse represents the location of the auditory cue. Standard errors of RTs are indicated by the vertical lines.

Two planned paired sample *t*-tests were conducted at each cue eccentricity with the RT data from those trials in which the cue and target were presented from the same hemifield. When the auditory cues were presented from the inner eccentricity, RTs were significantly faster when the visual targets were presented from the same position (M = 369ms) than from a different lateral position within the cued hemifield (M = 411ms), $t(21) = -5.553$, $p < .001$. When the cues were presented from the outer eccentricity, however, RTs were significantly *slower* when the targets were presented from the same position (M = 391ms) than from a different lateral position within the cued hemifield (M = 379ms), $t(21) = 2.620$, $p = .016$. In summary, the expected within-hemifield spatial cuing effect was documented only when the cues were presented from the inner eccentricity (see Figure 4.5).

A RM-ANOVA with the within-participants factor of Between-hemifield Spatial Cuing was conducted in order to investigate whether there was a between-hemifield spatial cuing effect. The analysis revealed a significant main effect of Between-hemifield Spatial Cuing, $F(1, 21) = 35.614$, $MSE = 81.105$, $p < .001$, $\eta_p^2 = .629$, with participants responding more rapidly to targets when the cue was presented from the same (M = 388ms) rather than the opposite (M = 404ms) side of fixation (see Figure 4.6).

ER data analysis

A RM-ANOVA with the two within-participants factors of Cue Location and Target Location revealed a significant main effect of Target Location, $F(3, 63) = 7.464$, $MSE = .001$, $p < .001$, $\eta_p^2 = .262$. The participants made significantly more errors with the outer-left visual targets (M = 2.3%) than with the inner-left targets (M = 0.9%), $t(21) = 3.334$, $p = .003$. Furthermore, the participants made significantly more errors when targets were presented from the outer-right position (M = 2.5%) than when presented

from the inner-right position (M = 0.6%), $t(21) = -2.871$, $p = .009$. The average ER was 1.6%, with the maximum ER of 3.8% and the minimum ER of 0.0%.

4.3.3. Discussion

As in Experiment 7, the standard between-hemifield spatial cuing effect was confirmed in Experiment 8. Furthermore, a significant within-hemifield spatial cuing effect was observed only when the auditory cues had been presented from the inner eccentricity. When the auditory cues were presented from the outer eccentricity, the data failed to demonstrate the expected within-hemifield spatial cuing effect. What is more, following the presentation of an auditory cue from the outer eccentricity, RTs to targets were significantly *slower* when the cue and target were presented from the same lateral position than when they were presented from different lateral positions within the cued hemifield. Such findings add further weight to the claim that the within-hemifield spatial cuing effect only from the inner auditory cues might simply reflect the interaction between the eccentricity effect and the between-hemifield spatial cuing effect. Indeed, the participants responded significantly more rapidly (and accurately) to the inner targets than to the outer targets regardless of cue location.

Experiment 9 was designed to further investigate the spatial specificity of cuing effects. All of the stimuli were now presented within 20° laterally from the fixation to potentially reduce the lateral eccentricity confound on spatial cuing (Carrasco et al., 1995; Carrasco & Frieder, 1997). It was initially suspected that the magnitude of spatial cuing effects could decrease due to the spatial proximity of the stimuli (e.g., the closer lateral distances between stimuli than those in Experiments 7 & 8). However, the evidence suggests that humans can discriminate the relative locations of two auditory cues when they are laterally separated by 1° (see Perrott & Saberi, 1990). Given that the inner and

outer locations will be separated by a visual angle of 10°, I expected that the results of Experiment 9 would be similar to those already reported in Experiments 7 and 8.

4.4. Experiment 9

4.4.1. Methods

4.4.1.1. Participants

Twenty participants from the OPR took part in this experiment (four male and sixteen female) with their average age of 26 years, ranging from 19 to 35 years. All of the participants self-reported normal or normal-to-corrected vision, and normal hearing. They were all right-handed. Experiment 9 took approximately 30 minutes to complete. All of the participants were paid £5 at the end of the experiment.

4.4.1.2. Apparatus, materials, design, and procedure

These were identical to those in Experiment 8 with the following exceptions: (1) The participants' eyes were approximately 77cm away from the fixation LED; (2) all four loudspeakers were placed next to each other, creating a 40° auditory cue range between the left wall of the far left loudspeaker and the right wall of the far right loudspeaker (56cm); (3) two target LEDs were installed 5.5cm above and below the centre of each loudspeaker cone, with approximately 8° of the vertical viewing angle. The inner and outer visual targets were placed approximately 5° (7cm) and 15° (21cm) from the fixation LED on each side (see Figure 4.3).

4.4.2. Results

All of the participants responded to over 95% of the total trials. The median of the participants' average RTs across all conditions was 375ms, with 351ms as Q_1 and 427ms as Q_3. The median of the participants' average ERs across all conditions was 0.5%, with 0.3% as Q_1 and 1.2% as Q_3. Three participants' ERs (Ms = 3.1%, 3.5%, and 9.4%) were above the upper limit (M = 2.5%) based on the Tukey's (1977) method, and were therefore removed from the data analysis. A total of 58 trials (1.2%) were removed from the data analyses based on the error response exclusion criteria used in Experiments 7 and 8.

RT data analysis

The mean RTs to visual targets following the presentation of an auditory cue either from the outer-left, outer-right, inner-left, or inner-right position are summarised in Figure 4.8. The within-participants factors of Cue Location and Target Location were entered into a RM-ANOVA, and this revealed a significant main effect of Target Location, $F(3, 48) = 18.412$, $MSE = 349.604$, $p < .001$, $\eta_p^2 = .535$. Once again, the participants responded significantly more rapidly to the targets presented from the inner-left position (M = 388ms) than from the outer-left position (M = 401ms), $t(16) = 5.187$, $p < .001$. RTs to the targets presented from the inner-right (M = 384ms) were also significantly faster than those from the outer-right (M = 404ms), $t(16) = -7.288$, $p < .001$. There was also a significant interaction between Cue and Target Location, $F(9, 144) = 10.251$, $MSE = 231.939$, $p < .001$, $\eta_p^2 = .390$, indicating the presence of a significant audiovisual spatial cuing effect.

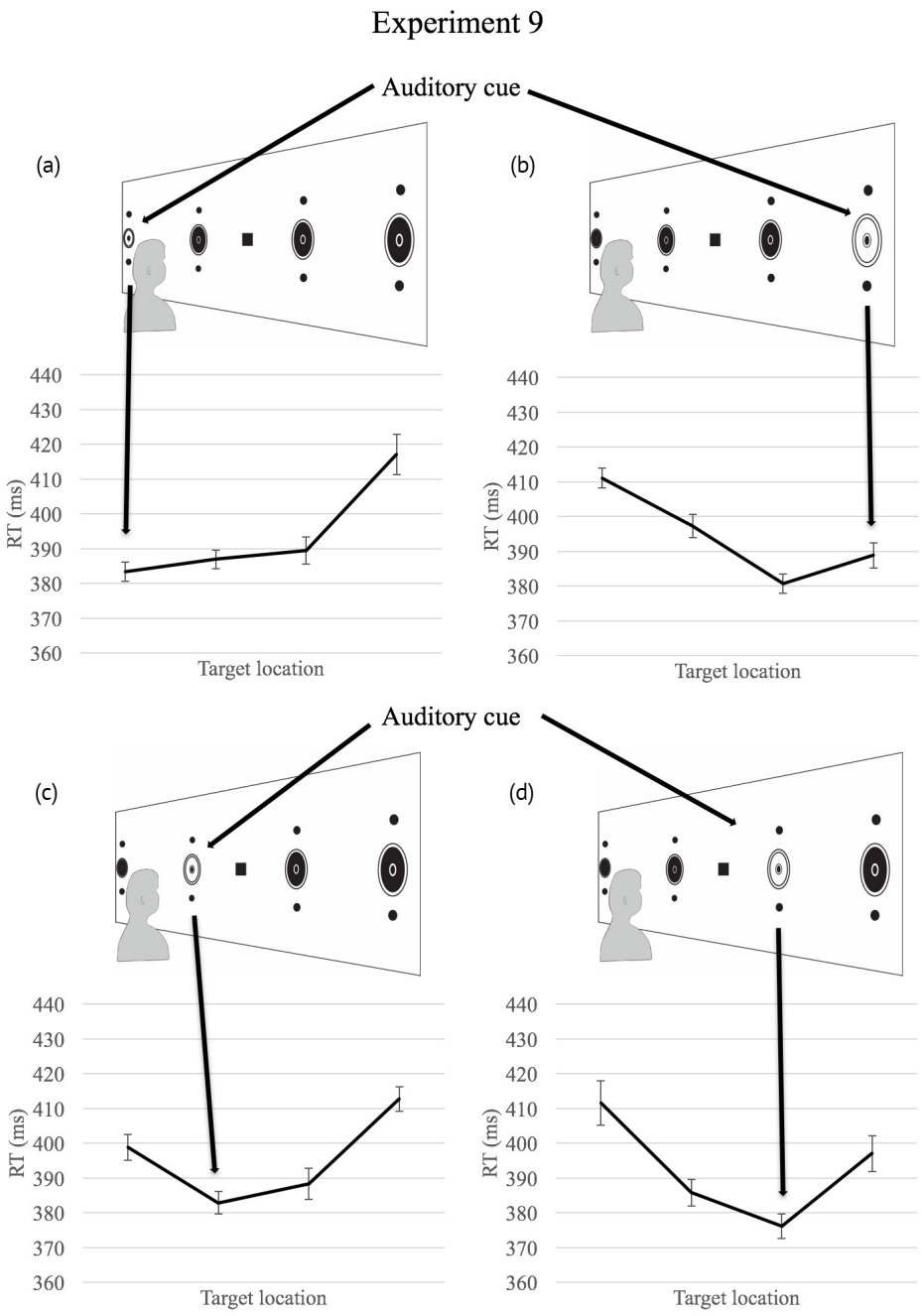


Figure 4.8. Mean reaction times (RTs) in milliseconds (ms) for Cue Location at the (a) outer-left, (b) outer-right, (c) inner-left, and (d) inner-right as a function of the Target Location in Experiment 9. The black dots and square represent the visual LEDs and the fixation LED, respectively. The ellipses represent the loudspeaker locations, and the bright one represents the auditory cue location. Standard errors of RTs are indicated using the vertical lines.

Two planned paired sample *t*-tests were conducted in order to test for within-hemifield spatial cuing effects. The analyses revealed that when the auditory cues were presented

from the inner eccentricity, RTs were significantly faster when the visual targets were presented from the same position (M = 380ms) than from a different lateral position within the cued hemifield (M = 398ms), $t(16) = -6.921$, $p < .001$. When the cues were presented from the outer eccentricity, however, RTs to targets presented from the same position (M = 386ms) were not statistically different compared to those presented from a different lateral position within the cued hemifield (M = 383ms), $t(16) = .743$, $p = .468$. Once again, the expected within-hemifield spatial cuing effect was documented only when the cues were presented from the inner eccentricity (see Figure 4.5). A RM-ANOVA with the within-participants factor of Between-hemifield Spatial Cuing revealed a significant main effect of Between-hemifield Spatial Cuing, $F(1, 16) = 31.327$, $MSE = 59.476$, $p < .001$, $\eta_p^2 = .662$, with participants responding significantly more rapidly to targets when the cue was presented from the same (M = 387ms) rather than the opposite (M = 402ms) hemifield (see Figure 4.6).

ER data analysis

The RM-ANOVA with the two within-participants factors of Cue Location and Target Location did not reveal any significant terms.

4.4.3. Discussion

As in Experiments 7 and 8, the results of Experiment 9 confirmed the standard between-hemifield spatial cuing effect. The findings of the within-hemifield spatial cuing effect were similar to those reported in Experiments 7 and 8. Following the presentation of an auditory cue from the inner eccentricity, the participants responded significantly more rapidly to the targets presented from the same position than to those from a different lateral position within the cued hemifield. However, no such within-hemifield spatial

cuing effect was found when the auditory cues were presented from the outer eccentricity.

It is noteworthy that RTs to the inner targets were significantly faster than those to the outer targets no matter where the auditory cues were presented from. In fact, the participants in all three of the experiments reported in this chapter responded significantly more rapidly to the inner targets than to the outer targets, regardless of the spatial cuing condition. Therefore, even though the small experiment set-size should have, at least in theory, mitigated the eccentricity effect, the data in Experiment 9 suggests that the documented within-hemifield cuing effects cannot be explained by the spatially-specific attentional shift following the presentation of an auditory cue.

4.5. General discussion

The results of the three experiments reported in this chapter add further weight to the suggestion that the presentation of a spatially-uninformative, task-irrelevant auditory cue can facilitate the perception of visual targets presented from the same rather than opposite hemifield. However, the results provide evidence against the conventional view concerning the spatial specificity of crossmodal audiovisual cuing effects, particularly from those trials in which the auditory cues were presented from the outer eccentricity. Furthermore, all three experiments demonstrated that RTs to the inner targets were significantly faster than those to the outer targets regardless of the cue location, thus confirming the existence of the eccentricity confound (see Figure 4.9). Therefore, the documented within-hemifield spatial cuing effects on those trials in which the auditory cues were presented from the inner locations could simply reflect an eccentricity effect.

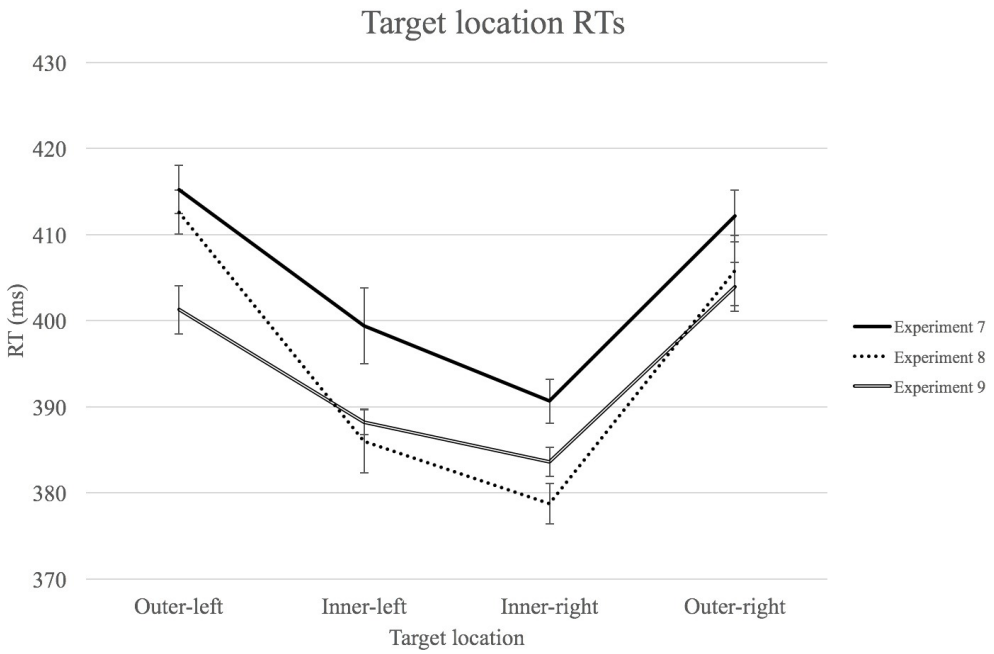


Figure 4.9. Mean reaction times (RTs) in milliseconds (ms) in Experiments 7 (solid-line), 8 (dotted-line), and 9 (double-line) as a function of the Target Location. Standard errors of mean RTs are indicated by the vertical lines.

One potential factor of the eccentricity confound is the difference in spatial resolution between the fovea and the periphery of the retina (see DeValois & DeValois, 1991). One of the major areas that ganglion cells project from retina is to lateral geniculate nucleus (and also to the SC), which then relays the information to primary visual cortex (V1; DeValois & DeValois, 1991).[16] However, ganglion cell density decreases as a function of the retinal eccentricity increase (from the fovea; Fischer, 1973). When the retinal projection finally arrives at V1, the cortical map reflects the logarithmic magnification of the retinal representation (see Tootell, Silverman, Switkes, & De Valois, 1982). Indeed, Carrasco and Frieder (1997) demonstrated in their visual search study that the eccentricity effect could be eliminated if the stimuli on the screen were scaled by the cortical magnification factor (CMF; Rovamo & Virsu, 1979; Virsu & Rovamo, 1979).

[16] It is worth noting that the SC receives inputs from ganglion cells as well as from various cortical areas including V1 (see Collins, Lyon, & Kaas, 2005). As a result, the cortical magnification in V1 could potentially influence how the multisensory neurons in the SC respond to the visual targets in audiovisual cuing studies.

In order to explain the documented within-hemifield spatial cuing effects reported in this chapter, I looked into the properties of the SC as I did in Chapter 3. Based on data from anaesthetised cat model, Meredith and Stein (1996) reported that the RFs of audiovisual SC neurons responsive to the frontal space exhibited visual RFs aligned centrally within the auditory RFs. However, for those neurons with RFs falling in lateral space, the visual RFs tended to be pushed close to, or over the medial border of auditory RFs (Meredith & Stein, 1996; see also Wallace & Stein, 2007). Therefore, it is possible to elicit response enhancement even when the auditory cues were presented from the outer location and the visual targets were presented from the inner location in the same hemifield, but not the other way around (see Figure 4.10).

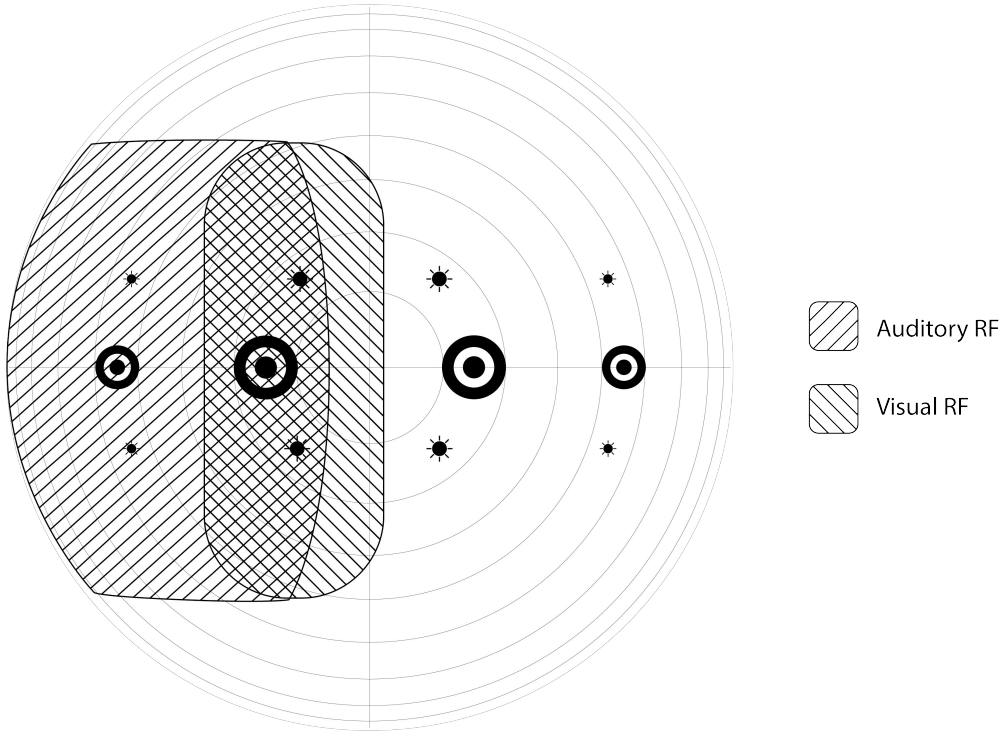


Figure 4.10. Schematic RF spatial registry of a SC single audiovisual neuron found in the peripheral sensory space. The horizontal and vertical lines represent 0° azimuth and 0° elevation, respectively, and each concentric circle 10° of space. Note that the auditory RF, although maintaining a considerable overlap with the visual RF, is located toward the peripheral sensory space. The illustration is based on the figures reported in Meredith and Stein (1996; also see Kadunce et al., 2001).

Neurophysiological studies in animals further suggest that multisensory neurons in the SC can vary widely in size depending on their location. For example, multisensory neurons in the rostral portion of the cat SC have been reported to have RFs often less than 10° for visual and 20° for auditory in diameter (see Kadunce et al., 2001). On the other hand, multisensory neurons in the caudal SC have visual RFs ranging from 40 to 100° and auditory RFs from 60 to 135° in diameter. Therefore, the attentional shift from the centre elicited by the auditory cues from the inner locations could potentially be more spatially-specific than from the outer locations, as demonstrated in all three experiments reported in this chapter. In conclusion, at least in theory, the findings on within-hemifield spatial cuing effects could be attributable to the correspondence patterns of audiovisual RFs in the SC, the eccentricity effect, or both. The response properties of audiovisual RFs in the SC, in particular, provide a useful theoretical perspective that can account for both the within-hemifield cuing effects reported in this chapter as well as the rear-to-front crossmodal spatial cuing effects reported in Chapters 2 and 3.

The results of the three experiments reported in the present chapter suggest that the presentation of an auditory cue does not always elicit faster RTs to visual targets presented from the same position rather than from a different lateral position within the cued hemifield. Regarding the spatial specificity of within-hemifield cuing effects, there are two questions remaining that are undoubtedly worthy of investigation. The first question is: Are *cuing benefits,* calculated by subtracting the current RTs from the baseline RT to targets at each eccentricity, spatially-specific? If audiovisual cuing effects without the eccentricity confound are, in fact, spatially-specific, the cuing benefits should be larger when the cue and target stimuli are presented from the same, rather than from different lateral positions within the cued hemifield. The second question is: Can the target perception be facilitated maximally following the presentation of an auditory

cue from the same position rather than from a different position within the target hemifield? The spatial specificity of within-hemifield cuing effects has been understood in terms of how the presentation of an auditory cue from a given position would modulate RTs to cued compared to uncued targets *within the cued hemifield* (see Driver & Spence, 1998; Spence et al., 2004; Spence & McDonald, 2004; see also Figure 4.2). On the other hand, the latter question focuses on how the RTs to visual targets would be modulated by the presentation of an auditory cue either from the same position or from a different lateral position *within the target hemifield*. With those two questions in mind, I decided to re-investigate the spatial specificity of within-hemifield cuing effects without the target eccentricity confound.

In order to test the spatially-specific cuing benefit hypothesis, I first calculated cuing benefits for each participant based on his/her average RT to targets at each eccentricity. The data were then collapsed across Experiments 7 and 8.[17] The outliers that were previously identified based on the Tukey's (1977) method were also excluded from the following analysis. Two sets of planned paired sample *t*-tests were conducted in order to re-examine within-hemifield spatial cuing effect using the cuing benefit data: one for Experiments 7 and 8, and another for Experiment 9.

Planned paired sample *t*-tests for the pooled RT data from Experiments 7 and 8 revealed that when the auditory cues were presented from the inner eccentricity, cuing benefits were significantly larger when the visual targets were presented from the same position (M = 11ms) than from a different lateral position within the cued hemifield (M = 1ms), $t(40) = 3.324$, $p = .002$. When the cues were presented from the outer eccentricity, cuing benefits were also significantly larger when the targets were presented from the same

[17] The data from Experiment 9 were analysed separately due to the lateral eccentricity differences between Experiments 7-8 and Experiment 9.

position (M = 18ms) than from a different lateral position within the cued hemifield (M = 3ms), $t(40) = 4.409$, $p < .001$. Another set of planned paired sample *t*-tests for Experiment 9 revealed that when the cues were presented from the inner eccentricity, there was a non-significant trend for the cuing benefits to be larger when the targets were presented from the same position (M = 6ms) than from a different lateral position within the cued hemifield (M = 4ms), $t(16) = 1.028$, $p = .319$. When the cues were presented from the outer eccentricity, the spatial cuing benefits were significantly larger when the targets were presented from the same position (M = 17ms) than from a different lateral position within the cued hemifield (M = 3ms), $t(16) = 3.804$, $p = .002$.

Two planned paired sample *t*-tests were conducted to investigate whether the perception of visual targets can be facilitated maximally when the auditory cues were presented from the same position rather than from a different lateral position within the target hemifield. Planned paired sample *t*-tests for the pooled RT data from Experiments 7 and 8 revealed that the RTs to inner targets were faster when the cues were presented from the same position (M = 377ms) than from a different lateral position within the target hemifield (M = 386ms), $t(40) = -2.534$, $p = .015$. Similarly, RTs to outer targets were faster when the cues were presented from the same position (M = 393ms) than from a different lateral position within the target hemifield (M = 410ms), $t(40) = -4.254$, $p < .001$. The same analyses for Experiment 9 revealed that RTs to inner targets were faster (although not significantly) when the cues were presented from the same position (M = 380ms) than from a different lateral position within the target hemifield (M = 383ms), $t(16) = -1.208$, $p = .244$. RTs to the outer targets were significantly faster when the cues were presented from the same position (M = 386ms) than from a different lateral position within the target hemifield (M = 398ms), $t(16) = -4.256$, $p = .001$.

The re-analyses revealed that the magnitude of response facilitation for visual targets was largest statistically-speaking when auditory cues are presented from the same position, except when the lateral eccentricity of the cue and target is 5° from fixation on each side. The lack of significant within-hemifield spatial cuing benefit/effect in Experiment 9 from the inner eccentricity suggests that there is little advantage of auditory spatial cuing for visual targets close to the current direction of gaze. Furthermore, the magnitude of cuing benefit/effect was larger from the outer eccentricity than from the inner eccentricity in all three experiments. In summary, the presentation of a spatially-uninformative auditory cue *does not* always lead to faster RTs to visual targets presented from the same position as compared to those from a different lateral position within the cued hemifield. However, the perception of visual targets is maximally facilitated when auditory cues are presented from the same position regardless of the cue-target eccentricity.

Taken together, the results of the three experiments reported here add further support for the existence of spatial cuing effects between hemifields. Additionally, the present study in this chapter provides the first empirical evidence on the spatial specificity of exogenous audiovisual cuing effects within the cued hemifield without a potential response bias confound. These findings may have real-world applications, such as developing an in-vehicle auditory warning system (Lee, Olsen, & Wierwille, 2004; see Ho & Spence, 2008; Spence & Ho, 2015). Between-hemifield spatial auditory cuing should be able to facilitate response to visual targets (e.g., potential dangers on the road) on the cued side. However, if even greater facilitation of the response to a target is desired, an auditory warning cue should be presented from a specific location that is in the direction of a frontal visual target (e.g., Ho & Spence, 2005). If the auditory warning system can accommodate only one auditory alarm position on each side, vehicle

operators would benefit more if the warnings were designed to assist them to be aware of visual targets presented further away from, rather than close to, the central gaze.

Chapter 5. Assessing the influence of auditory cue parameters on crossmodal cuing in different regions of space

5.1. Introduction

Despite the extensive body of research on exogenous audiovisual spatial attention that has been published to date, most studies have investigated how the positioning of auditory cues would modulate spatial attention crossmodally. That is, there has been little consideration as to how, and even whether, parameters of the auditory cue, such as its duration, intensity change, and waveform structure might modulate the crossmodal spread of attention. Rather unexpectedly, the results of Experiment 3 (in Chapter 2) have already demonstrated that sound parameters can influence crossmodal spatial attention and even increase the magnitude of crossmodal spatial cuing effects. The presentation of a 1,000ms looming white noise cue elicited a larger crossmodal spatial cuing effect when the cues were presented from the front than when the cues were presented from the rear. Furthermore, the magnitude of the crossmodal spatial cuing effect following the presentation of the 1,000ms looming white noise cues in Experiment 3 was considerably larger than that from the 50ms constant-intensity cues in Experiment 2 (18 vs. 5ms, respectively).

Despite the potential advantage of using looming white noise cues to exogenously orient crossmodal spatial attention as demonstrated in Experiment 3, it should be noted that the intensity of the looming cue ramped up exponentially from silence to 80dBA. Therefore,

as mentioned previously in Chapter 2 (see Footnote 11), the perceived duration of the looming white noise cues in Experiment 3 would have been less than 1,000ms, unlike that of the constant-intensity auditory cues. As a result, one could argue that the spatially-specific crossmodal cuing effect documented with the looming white noise cues might simply have been due to the extended SOAs that were used. However, it is unlikely that the extended SOA alone contributed to eliminating the rear-to-front crossmodal spatial cuing effect in Experiment 3, as the SOAs up to 700ms failed to modulate the crossmodal spatial cuing effects in Experiments 2 and 5 (Chapters 2 & 3, respectively).

Perhaps, then, the spatially-specific cuing effect elicited by the 1,000ms looming auditory cues was attributable to the cues being more effective in exogenously orienting participants' spatial attention narrowly to the cued region of space than other types of cue. In fact, looming sounds have often been considered as a salient cue for an organism's survival (e.g., Maier & Ghazanfar, 2007; Neuhoff, 1998, 2001). However, it is unclear, yet, as to what really contributed to eliciting such a spatially-specific cuing effect: the exponential increase in intensity or the exponential change in intensity. Will the presentation of a *receding* white noise (i.e., an exponentially decreasing intensity) auditory cue also elicit such a spatially-specific crossmodal cuing effect? Previous studies have demonstrated that the presentation of a *structured* (i.e., triangle waveform; see Leo, Romei, Freeman, Ladavas, & Driver, 2011; Romei, Murray, Cappe, & Thut, 2009) looming sound could elicit stronger perceptual biases than a receding structured sound might do (e.g., Ghazanfar, Neuhoff, & Logothetis, 2002; Leo et al., 2011; Neuhoff, 1998, 2001).[18] However, such an asymmetry in the perceptual biases for

[18] The perceptual biases towards structured looming sounds have been demonstrated in terms of, for instance, the duration of behavioural orienting responses (in rhesus monkeys; Ghazanfar et al., 2002), visual orientation discrimination sensitivity (with human participants; Leo et al., 2011), overestimating the

looming sounds in preference to receding sounds from structured tones was eliminated when white noise sounds were used. Therefore, it is possible that receding white noise cues could be as effective as looming white noise cues in exogenously orienting spatial attention.

Experiment 10 was designed to confirm the lack of perceptual bias between looming white noise and receding white noise cues, and the asymmetric perceptual bias between looming structured and receding structured cues in crossmodal spatial cuing effects. More specifically, the following hypotheses were tested: The first hypothesis was that the presentation of either a looming white noise, receding white noise, or a looming structured cue would elicit a spatially-specific cuing effect. However, a rear-to-front crossmodal spatial cuing effect was expected following the presentation of a receding structured auditory cue. The second hypothesis was that the magnitude of a crossmodal spatial cuing effect would be larger in the looming structured cue condition than in the receding structured cue condition. The third hypothesis was that the magnitude of a crossmodal spatial cuing effect in the looming white noise cue condition would not be statistically different from that observed in the receding white noise cue condition.

Experiment 10 was divided into two sections: the exogenous crossmodal spatial cuing task and the sound location discrimination task. All of the participants took part in the spatial cuing task first, and then the sound location discrimination task. The sound location discrimination task was conducted in order to investigate whether the sound parameters would influence the participants' performance in discriminating the location of auditory stimuli used in the exogenous crossmodal spatial cuing task. The design of the exogenous crossmodal spatial cuing task involved four within-participants factors:

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change in sound intensity (with human participants; Neuhoff, 1998, 2001), and underestimating the arrival time of an approaching sound (with human participants; Neuhoff, Planisek, & Seifritz, 2009).

Cue Position (front vs. rear), Cue Type (looming vs. receding)[19], Cue Structure (structured vs. white noise), and Spatial Cuing (cued vs. uncued), and one between-participants factor: Cue Duration (250 vs. 500ms).[20] To analyse the RT data, the five factors were entered into a mixed ANOVA. An equivalent mixed ANOVA was subsequently conducted with the ER data in order to investigate whether there was any speed-accuracy trade-off in any form of spatial cuing effects (Duncan, 1980; Spence et al., 2000). The details of the sound location discrimination task will be discussed following the data analysis from the exogenous crossmodal spatial cuing task.

5.2. Experiment 10

5.2.1. Exogenous crossmodal spatial cuing task

5.2.1.1. Methods

5.2.1.1.1. Participants

Forty-four (fifteen male and twenty-nine female) took part in this experiment. They were recruited via the Crossmodal Research Laboratory mailing list, the OPR, and the RPS. Their average age was 26 years, ranging from 18 to 49 years. All of the participants reported normal (or corrected-to-normal) vision and hearing. All were right-handed by self-report. The participants were randomly assigned to one of two Cue Duration conditions. The experiment lasted for approximately 30-40 minutes depending on the duration of the cue. At the end of the study, the participants were either given two course

[19] The intensity of looming and receding auditory cues varied between 55-75dBA as measured from the participant's head position. Since auditory stimuli above 15dB SPL are all audible (see Sabin et al., 2005), the perceived onset timing of a receding cue should be identical to that of a looming cue.

[20] The between-participants factor of Cue Duration was included in the study design in order to test whether the cue durations would modulate exogenous crossmodal spatial cuing effects differently. However, no significant modulation effect from Cue Duration was expected on the exogenous orienting of crossmodal spatial attention (cf. Romei et al., 2009).

credits for having taken part in the study, or else paid £7 if assigned in the 500ms Cue Duration condition or £5 in the 250ms Cue Duration condition.

5.2.1.1.2. Apparatus and materials

The experiment was conducted in a darkened room using MATLAB R2014a with PSYCHTOOLBOX 3.0.12 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). The participants were seated facing a red LED (identical to that used in Experiments 4-9) as a fixation point with a computer keyboard on their lap. The same computer monitor used in Experiments 4-9 was placed below the fixation LED to display instruction screens. On each side of the fixation point, there was a loudspeaker (identical to that used in Experiments 7-9) at eye-level (117cm above the floor). Two additional loudspeakers were placed behind the participant's head, parallel to the front loudspeakers. The front and rear loudspeakers were separated by 128cm, and the left and right loudspeakers by 74cm, both measured from the centres of each single-cone (see Figure 5.1). All four loudspeakers were connected to the same USB audio interface used in Experiments 1-9.

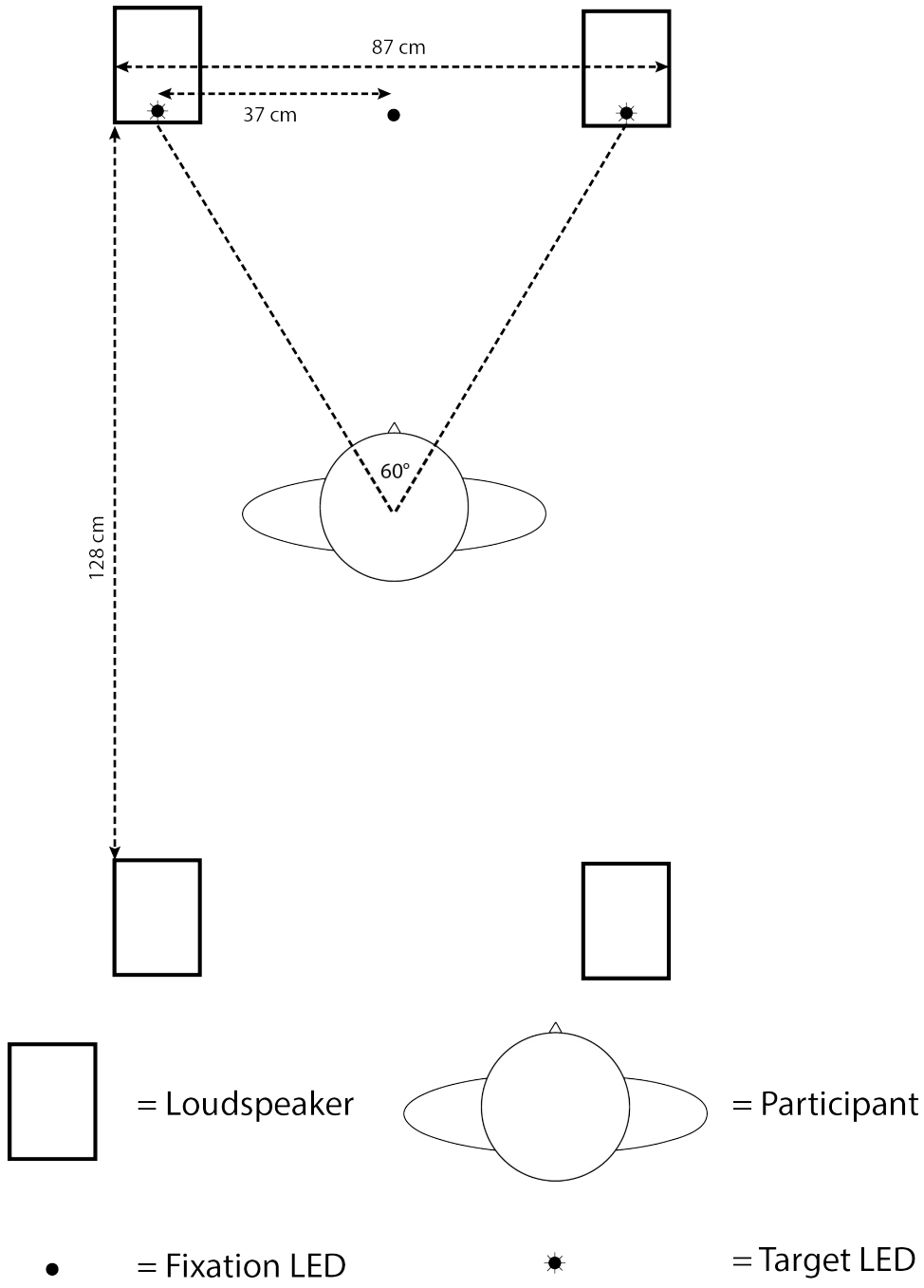


Figure 5.1. Bird's-eye view of the placement of the four loudspeakers, visual target location (only top two of four shown), and the fixation point in relation to the participant in Experiment 10.

Two red target LEDs (the same as the fixation LED) were placed on each side, 9cm above and below each loudspeaker, as measured from the centre of the single-cone. Auditory stimuli, sampled at 44.1kHz, were created with Adobe Audition CC 2015. Structured tonal cues were 400Hz triangular waveforms (similar to those used by Leo et

al., 2011; Romei et al., 2009). Looming sounds exponentially changed intensity from 55 to 75dBA, and receding sounds from 75 to 55dBA, as measured from the participant's head position. Each auditory cue was generated by using the same procedure described above, instead of manipulating the sound parameters of another auditory cue. The auditory cues had 5ms onset and offset ramps to avoid clicks.

5.2.1.1.3. Design

The study design consisted of four within-participants factors: Cue Position, Cue Type, Cue Structure, and Spatial Cuing, and a between-participant factor: Cue Duration. Crossing the four within-participants factors yielded 16 possible conditions, with each condition being presented pseudo-randomly 24 times. Each participant completed three blocks of 128 trials. The participants were given a chance to take a short break between blocks.

5.2.1.1.4. Procedure

Each trial started with the illumination of the fixation LED. After a random delay of 400-650ms, a spatially-nonpredictive auditory cue was presented from one of the four possible locations: front-left, front-right, rear-left, or rear-right. Following the offset of the auditory cue, there was a random delay of 100-200ms before the onset of a visual target. The duration of any random delay on each trial was chosen from the discrete uniform distribution. The SOA was therefore 350-450ms and 600-700ms in the 250ms and 500ms Cue Duration conditions, respectively. The visual target was presented for 140ms from one of four possible corner locations: top-left, top-right, bottom-left, or bottom-right. Using the computer keyboard, the participants pressed the *up* arrow key if the target was presented from either the top-left or the top-right, or the *down* arrow key if

the target was presented from either the bottom-left or the bottom-right as rapidly and accurately as possible. Once the participant's response had been registered, or else if the participant had not responded in the 2,000ms after the onset of the visual target, the illumination of the fixation was terminated and the next trial began. The instructions were provided on the computer screen in front of the participant, below the fixation light. Following the presentation of the instruction screen, the participants completed ten practice trials. The experimenter answered any questions that the participant might have had, and then left the experimental room before the actual experimental trials began. When the target elevation discrimination study was completed, the experimenter re-entered the room and asked the participant if she/he needed a break before proceeding to the sound location discrimination task (see Section 5.2.2).

5.2.1.2. Results

Participants who failed to respond to over 95% of the total trials were excluded from the data analysis. One participant failed to respond 10% of the total trials, and was therefore excluded from the data analysis. A box-plot of the participants' mean RTs revealed a median of 365ms, with 339ms and 401ms as Q_1 and Q_3, respectively. Another box-plot of the participants' ERs revealed a median of 1.3%, with 0.5% and 2.6% as Q_1 and Q_3, respectively. Based on the Tukey's (1977) method, two participants' mean RTs (Ms = 500ms, 580ms) and two other participants' mean ERs (Ms = 6.5%, 48.5%) were above the upper limits (Ms = 495ms and 5.7%, for the mean RT and the mean ER, respectively), and were therefore removed from the further data analysis. Lastly, the subsequent trials were further excluded from the remaining data: trials with incorrect responses, responses immediately following an incorrect response, no response trials, and trials with target RTs slower than 1,500ms or faster than 150ms (see Chapters 3 and

4, for similar exclusion criteria). The application of the third exclusion criterion resulted in the removal of 454 trials (3.0% of the remaining data). The mean RT and ER for each condition in Experiment 10 are summarised in Table 5.1.

Table 5.1.

Mean Reaction Times (RTs) and Standard Errors (SEs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) in the exogenous crossmodal spatial cuing task of Experiment 10.

Cue position	Cue type	Cue structure	Spatial cuing	Cue duration (ms)	RTs (ms)	SEs (ms)	ERs (%)
Front	Looming	Structured	Cued	250	351	4	1.0
				500	362	4	1.1
			Uncued	250	370	3	1.5
				500	379	3	2.4
		White noise	Cued	250	360	4	0.6
				500	371	4	1.3
			Uncued	250	380	5	3.3
				500	392	5	1.3
	Receding	Structured	Cued	250	357	4	0.8
				500	381	4	1.8
			Uncued	250	364	4	1.5
				500	380	4	2.6
		White noise	Cued	250	354	4	1.3
				500	373	5	0.4
			Uncued	250	369	4	1.0
				500	391	4	0.9
Rear	Looming	Structured	Cued	250	354	5	1.7
				500	375	3	2.4
			Uncued	250	365	3	1.5
				500	375	4	2.0
		White noise	Cued	250	366	4	0.8
				500	376	4	0.9
			Uncued	250	370	4	1.3
				500	389	6	1.5
	Receding	Structured	Cued	250	361	4	1.3
				500	384	5	1.5
			Uncued	250	365	4	1.9
				500	384	5	2.0
		White noise	Cued	250	360	4	1.5
				500	387	4	2.0
			Uncued	250	373	4	1.5
				500	391	4	1.8

5.2.1.2.1. RT data analysis

A mixed ANOVA was conducted with the within-participants factors of Cue Position, Cue Type, Cue Structure, and Spatial Cuing, and the between-participants factor of Cue Duration. The analysis revealed a significant main effect of Cue Position, $F(1, 37) = 4.205$, $MSE = 307.921$, $p = .047$, $\eta_p^2 = .102$, with participants responding more rapidly to the frontal visual targets following the presentation of an auditory cue in the front (M = 370ms) than the rear (M = 373ms). There was also a significant main effect of Cue Structure, $F(1, 37) = 7.321$, $MSE = 765.457$, $p = .010$, $\eta_p^2 = .165$, with participants responding more rapidly to the visual targets following the presentation of a structured auditory cue (M = 368ms) than following the presentation of a white noise cue (M = 374ms). More importantly, a significant main effect of Spatial Cuing was also documented, $F(1, 37) = 34.486$, $MSE = 492.312$, $p < .001$, $\eta_p^2 = .482$. RTs to targets were faster when the cue and target were presented from the same side (M = 366ms) rather than from different sides (M = 377ms).

There was a significant two-way interaction between Cue Position and Spatial Cuing, $F(1, 37) = 10.818$, $MSE = 251.190$, $p = .002$, $\eta_p^2 = .226$. Paired-comparisons with Bonferroni correction ($\alpha = .025$) revealed that this interaction was attributable to the larger magnitude crossmodal spatial cuing effect reported following the presentation of an auditory cue in the front than in the rear. In the frontal Cue Position condition, RTs to visual targets were significantly faster (by 15ms) in the cued (M = 363ms) than in the uncued condition (M = 377ms), $t(38) = -6.030$, $p < .001$. In the rear Cue Position condition, RTs to targets were significantly faster by 6ms in the cued (M = 370ms) than in the uncued (M = 376ms) condition, $t(38) = -3.337$, $p = .002$ (see Figure 5.2).

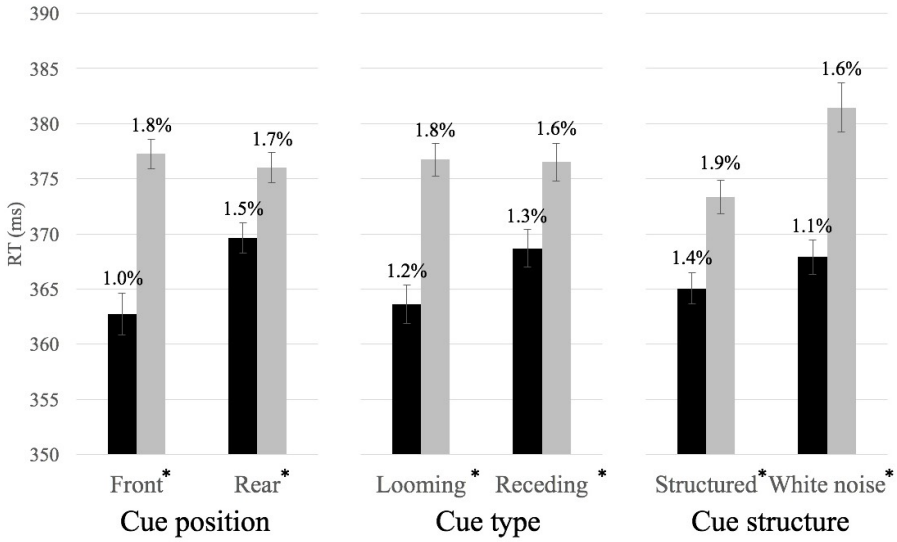


Figure 5.2. Mean reaction times (RTs) in milliseconds (ms) and error rates (%) as a function of the Cue Position, Cue Type, and Cue Structure in the exogenous crossmodal spatial cuing task of Experiment 10. Black bars represent the mean RTs in the condition in which the cue and target were presented from the same side. Grey bars represent the mean RTs in the condition in which the cue and target were presented from different sides. The asterisks indicate significant spatial cuing effects from the RT data based on pairwise comparisons (*t*-tests) with Bonferroni-adjusted alpha level of .025. Vertical lines indicate standard errors of mean RTs. An average error rate for each condition is provided as a percentage above the relevant standard error line.

The two-way interaction between Cue Type and Spatial Cuing was also significant, $F(1, 37) = 5.514$, $MSE = 202.843$, $p = .024$, $\eta_p^2 = .130$. This interaction was attributable to the larger magnitude crossmodal spatial cuing effect reported in the looming auditory cue condition (by 13ms, $t[38] = -6.530$, $p < .001$) than that in the receding cue condition (by 8ms, $t[38] = -3.525$, $p = .001$). Another significant two-way interaction was found between Cue Structure and Spatial Cuing, $F(1, 37) = 6.462$, $MSE = 236.093$, $p = .015$, $\eta_p^2 = .149$. Paired-comparisons with Bonferroni correction ($\alpha = .025$) revealed that with structured auditory cues, the magnitude of the spatial cuing effect was 7ms (365ms in the cued vs. 372ms in the uncued condition), $t(38) = -4.490$, $p < .001$. With white noise cues,

the magnitude of the spatial cuing effect was 13ms (368ms in the cued vs. 381ms in the uncued condition), $t(38) = -.5.143$, $p < .001$.

Other significant terms include a two-way interaction between Cue Type and Cue Duration, $F(1, 37) = 4.967$, $MSE = 561.493$, $p = .032$, $\eta_p^2 = .118$. This interaction can be attributed to RTs to visual targets following the presentation of a looming auditory cue (M = 376ms) being significantly faster than those following the presentation of a receding cue (M = 383ms) in the 500ms Cue Duration condition, $t(18) = -2.515$, $p = .022$. In the 250ms Cue Duration condition, however, RTs to the visual targets were not significantly different as a function of whether the intensity of the auditory cue was looming (M = 364ms) or receding (M = 363ms), $t(19) = .606$, $p = .552$. The interaction between Cue Type and Cue Structure, $F(1, 37) = 4.837$, $MSE = 311.109$, $p = .034$, $\eta_p^2 = .116$ also reached significance. Pairwise-comparisons revealed that with the looming cues, RTs to targets were faster following the presentation of a structured cue (M = 366ms) than following a white noise cue (M = 375ms), $t(38) = -3.765$, $p = .001$. With the receding cues, there was no significant difference in RTs to targets between the structured (M = 371ms) and white noise (M = 374ms) auditory cue conditions, $t(38) = -1.021$, $p = .313$.

No four-way interaction was found between Cue Position, Cue Type, Cue Structure, and Spatial Cuing, $F(1, 37) = 1.889$, $MSE = 318.314$, $p = .505$, $\eta_p^2 = .175$. Four planned paired sample *t*-tests were conducted in order to test the first hypothesis that only the presentation of a looming structured, looming white noise, or receding white noise cue would elicit a spatially-specific crossmodal cuing effect. The analysis revealed that the magnitude of a cuing effect in the looming structured front cue condition (M = 18ms) was significantly larger than that in the looming structured rear cue condition (M = 6ms),

$t(38) = -2.360$, $p = .024$. The magnitude of a cuing effect in the receding structured front cue condition (M = 3ms) was not statistically different from that in the receding structured rear cue condition (M = 3ms), $t(38) = -.004$, $p = .997$. The magnitude of a cuing effect in the looming white noise front cue condition (M = 21ms) was significantly larger than that in the looming white noise rear cue condition (M = 8ms), $t(38) = -2.269$, $p = .029$. The magnitude of the cuing effect in the receding white noise front cue condition (M = 17ms) was larger (although not significantly) than that in the receding white noise rear cue condition (M = 8ms), $t(38) = -1.633$, $p = .111$. Therefore, the findings of the exogenous crossmodal spatial cuing task conducted in Experiment 10 failed to confirm the first hypothesis.

A planned paired sample *t*-test was conducted between the magnitude of the crossmodal spatial cuing effect reported in the looming structured cue condition and that reported in the receding structured cue condition. The analysis revealed that the magnitude of the cuing effect reported in the looming structured cue condition (M = 12ms) was significantly larger than that reported in the receding structured cue condition (M = 3ms), $t(38) = -2.949$, $p = .005$. Therefore, the second hypothesis was confirmed. Another paired sample *t*-test was conducted between the magnitude of a crossmodal spatial cuing effect in the looming white noise cue condition and that obtained in the receding white noise cue condition. The analysis revealed that the magnitude of the cuing effect reported in the looming white noise cue condition (M = 15ms) was not statistically different from that seen in the receding white noise cue condition (M = 13ms), $t(38) = -.546$, $p = .588$. Therefore, the third hypothesis was also confirmed.

5.2.1.2.2. ER data analysis

An equivalent mixed ANOVA on the error data was conducted with the data from thirty-nine participants included in the RT data analysis. There was a significant main effect of Spatial Cuing, $F(1, 37) = 5.588$, $MSE = .001$, $p = .023$, $\eta_p^2 = .131$, with participants responding more accurately to visual targets in the cued (M = 1.3%) than in the uncued (M = 1.7%) condition, $t(38) = -2.400$, $p = .021$. A significant two-way interaction was found between Cue Position and Spatial Cuing, $F(1, 37) = 4.345$, $MSE < .001$, $p = .044$, $\eta_p^2 = .105$. Paired-comparisons with Bonferroni correction ($\alpha = .025$) revealed that when the auditory cues were presented from the frontal space, ERs in response to targets were significantly lower in the cued (M = 1.0%) than in the uncued (M = 1.8%) condition, $t(38) = -3.172$, $p = .003$. When the cues were presented from the rear, on the other hand, ERs in the cued (M = 1.5%) and uncued (M = 1.7%) conditions were not significantly different, $t(38) = -.654$, $p = .517$.

The analysis also revealed a three-way interaction between Cue Position, Cue Type, and Cue Structure, $F(1, 37) = 4.781$, $MSE = .001$, $p = .035$, $\eta_p^2 = .114$. Paired-comparisons with Bonferroni correction ($\alpha = .025$) revealed no meaningful results. The three-way interaction between Cue Position, Cue Structure, and Cue Duration was also significant, $F(1, 37) = 4.498$, $MSE < .001$, $p = .041$, $\eta_p^2 = .108$. The interaction was attributable to the participants' ERs being significantly larger in the structured cue condition (M = 2.0%) than in the white noise cue condition (M = 1.0%) when the 500ms cues were presented in front, $t(18) = 3.052$, $p = .007$. Other pairwise comparisons failed to yield any significant terms ($\alpha = .013$). Taken together, the spatial cuing effects documented in Experiment 10 would therefore appear to reflect a genuine attentional facilitation rather than a speed-accuracy trade-off (see Duncan, 1980; Spence et al., 2000).

5.2.2. Sound location discrimination task

5.2.2.1. Methods

5.2.2.1.1. Participants, apparatus, and materials

These were identical to those reported in the crossmodal spatial cuing task, except for the fact that the visual targets were not presented. Instead, the auditory cues used in Experiment 10 were now used as targets in this sound location discrimination task.

5.2.2.1.2. Design and procedure

There were three within-participants factors of Target Position (front vs. rear), Target Type (looming vs. receding), and Target Structure (structured vs. white noise), and a between-participant factor of Target Duration (250 vs. 500ms). Crossing the three within-participants factors yielded 8 conditions which were pseudo-randomly presented 8 times in a single block of 64 experimental trials. The procedure in each trial was identical to that of the Experiment 10 with the following exception: The participants had to discriminate the location of an auditory target by pressing *7, 9, 1*, and *3* for the target presented from the front-left, front-right, rear-left, and rear-right, respectively, on the keyboard number pad.

5.2.2.2. Results and discussion

Five participants excluded from the RT data analysis were also excluded from the following analysis. A mixed ANOVA was performed using the three within-participants factors and one between-participants factor. The analysis revealed a significant main effect of Target Position, $F(1, 37) = 32.082$, $MSE = .037$, $p < .001$, $\eta_p^2 = .464$, with ERs being higher for the targets presented from the rear (M = 16.9%) than from the front (M

= 4.7%). There was also a significant main effect of Target Structure, $F(1, 37) = 34.192$, $MSE = .030$, $p < .001$, $\eta_p^2 = .480$, with ERs being higher for the structured targets (M = 16.5%) than for the white noise targets (M = 5.1%). There was a significant two-way interaction between Target Position and Target Structure, $F(1, 37) = 16.791$, $MSE = .038$, $p < .001$, $\eta_p^2 = .312$. Pairwise comparisons with Bonferroni adjustment ($\alpha = .025$) revealed that when the auditory stimuli were presented from the front, ERs to structured targets (M = 5.8%) were not significantly different from white noise targets (M = 3.5%), $t(38) = 1.165$, $p = .251$. On the other hand, when the targets were presented from the rear, ERs to structured targets (M = 27.1%) were significantly higher than that to white noise targets (M = 6.7%), $t(38) = 5.592$, $p < .001$. The interaction between Target Type and Target Structure was also significant, $F(1, 37) = 7.358$, $MSE = .008$, $p = .010$, $\eta_p^2 = .116$. Pairwise comparisons with Bonferroni adjustment ($\alpha = .025$) revealed that for the structured targets, ERs in response to the looming targets (M = 18.2%) were significantly higher than those in response to the receding targets (M = 14.7%), $t(38) = 2.419$, $p = .020$. For the white noise targets, on the other hand, ERs were not significantly different between the looming (M = 4.2%) and receding (M = 6.1%) conditions, $t(38) = -1.821$, $p = .076$.

The results of the sound location discrimination task revealed that the participants made significantly more errors in response to the auditory targets presented in the rear than when presented from the frontal space (see Makous & Middlebrooks, 1990, for similar findings). The participants also made significantly more errors in response to the structured auditory targets (16.5%) than to the white noise targets (5.1%). Furthermore, the ERs were not statistically different between the structured and white noise conditions when the targets were presented from the front. By contrast, when the targets were presented from the rear, the participants made significantly fewer errors with the white

noise targets (6.7%) than with the structured tonal targets (27.1%). Such superior localizability of white noise as compared to structured tonal sound is consistent with the results of previous sound localisation studies (see Roffler & Butler, 1968; see also Spence & Driver, 1994). Table 5.2 summarizes the sound location discrimination responses, presented in a confusion matrix. As shown in Table 5.2, 97.8% of the total error responses were attributable to front-back confusion.

Table 5.2.

Confusion matrix for the number of responses participants made as a function of auditory target location in the sound location discrimination task of Experiment 10. Each cell's theoretical maximum is 624. The bold diagonal line represents the number of correct responses, and the underlined numbers indicate front-back confusions.

Auditory target location	Response			
	Front-left	Front-right	Rear-left	Rear-right
Front-left	**599**	1	21	2
Front-right	3	**590**	0	31
Rear-left	113	1	**509**	0
Rear-right	1	96	0	**527**

5.2.3. Discussion

The exogenous crossmodal spatial cuing study in Experiment 10 was designed to test the asymmetric perceptual bias for looming sounds from structured, in comparison to white noise, auditory cues. Three proposed hypotheses were evaluated in the exogenous crossmodal spatial cuing task. The first hypothesis was that spatially-specific crossmodal cuing effects would only be documented following the presentation of a looming structured, looming white noise, or receding white noise cue. The second hypothesis was

that the magnitude of any cuing effect in the looming structured cue condition would be larger than that reported in the receding structured cue condition. The third was that the magnitude of a crossmodal spatial cuing effect would be not different between the looming white noise cue condition and the receding white noise cue condition.

The data of the exogenous crossmodal spatial cuing task in Experiment 10 confirmed the second and third hypotheses, thus providing further evidence on the asymmetric perceptual bias for looming sounds from structured auditory stimuli (see Ghazanfar et al., 2002; Neuhoff, 1998, 2001). The first hypothesis was rejected, however, because the difference in magnitude of the cuing effect between the front and rear cue conditions failed to reach significance for the receding white noise cues. In other words, the asymmetric perceptual bias for looming sounds in preference to receding sounds was documented with the white noise cues. Such findings suggest that when white noise cues are used, the perceptual bias for looming sounds in preference to receding sounds may not completely disappear as had been suggested previously (e.g., Leo et al., 2011), at least in visual target elevation discrimination tasks involving both the front and rear space.

The main effect of Cue Structure documented in the exogenous crossmodal spatial cuing task in Experiment 10 indicates that the presentation of a structured auditory cue, regardless of its spatial location, can elicit a greater alerting effect (see Niemi & Näätänen, 1981; see also Petersen & Posner, 2012) than white noise cues. The alertness elicited by the presentation of a structured cue, however, seems to have resulted in greater ERs in response to visual targets (see Figure 5.2). What is more, the participants made significantly more errors with structured auditory targets (M = 16.5%) than with white noise targets (M = 5.1%) in the sound location discrimination task, mostly due to the greater front-back confusions with structured targets than with white noise targets.

The results of Experiment 10 therefore appear to suggest that the looming white noise may be more effective than looming structured cues in exogenously orienting crossmodal attention to the frontal or rear space.

Previously, in Experiments 2 and 5, the factor of SOAs (with the maximum of 700ms) did not modulate the reported rear-to-front crossmodal spatial cuing effects. Furthermore, no significant terms involving the factor of Cue Duration were documented in the exogenous crossmodal spatial cuing task of Experiment 10. Therefore, it is likely that the sound parameters, not the extended SOAs, contributed to eliminating the rear-to-front crossmodal spatial cuing effect following the presentation of a looming white noise or a looming structured cue. However, I decided to confirm once again that the spatially-specific crossmodal cuing effects reported in the exogenous crossmodal spatial cuing task of Experiment 10 were indeed due to the sound parameters not the extended SOAs. Experiment 11 was therefore designed to replicate the rear-to-front crossmodal spatial cuing effects reported in Experiments 2 and 5 using the same apparatus set-up as in Experiment 10, except using brief constant-intensity auditory cues. It was hypothesised that the presentation of a brief (i.e., 110ms) auditory cue would elicit a rear-to-front crossmodal spatial cuing effect regardless of the SOAs (i.e., 100, 250, or 500ms).

5.3. Experiment 11

5.3.1. Methods

5.3.1.1. Participants

Eighteen participants (7 male and 11 female) volunteered to take part in this experiment through the OPR and PRS. Their average age was 22 years, ranging from 18 to 33 years. All of the participants were right-handed, and had normal (or corrected-to-normal) vision

and hearing by self-report. The experiment lasted for approximately 30 minutes. At the end of the experiment, the participants were paid £5 or else given two course credits for having taken part in the study.

5.3.1.2. Apparatus and materials

These were the same as in Experiment 10, with the following exceptions. The experiment was conducted in a darkened (although not completely) room in University Club.[21] Auditory cues consisted of three 30ms bursts of white noise at 75dBA, measured from the participant's head position. Each burst of white noise was separated by 10ms silent gaps.

5.3.1.3. Design and procedure

The study design for Experiment 11 consisted of Cue Position, SOA (100, 250, or 500ms), and Spatial Cuing. Crossing the three within-participants factors yielded 12 possible conditions, with each condition presented pseudo-randomly 32 times. There were a total of three blocks of 128 trials. The procedure was identical to that in Experiment 10, except the new SOA conditions.

5.3.2. Results

All of the participants responded to over 95% of the total trials. A box-plot of the participants' mean RTs revealed a median of 418ms, with 357ms and 451ms as Q_1 and Q_3, respectively. Another box-plot of the participants' ERs revealed a median of 2.1%,

[21] The change of experimental room was necessitated by the sudden closure of the Tinbergen building on 13th February, 2017. The temporary experimental room provided in the University Club was naturally-lit with the sunlight, and the curtains provided in the room could not blackout the sun completely.

with 1.0% and 3.2% as Q_1 and Q_3, respectively. All participants' mean RTs and ERs were within the lower and upper limits based on the Tukey's (1977) method; no outliers were identified. The application of the exclusion criteria used in Experiment 10 resulted in the removal of 300 trials (4.4%). The average RT and ER for each condition in Experiment 11 are summarised in Table 5.3.

Table 5.3.

Mean Reaction Times (RTs) and Standard Errors (SEs) in milliseconds (ms) and Mean Error Rates (ERs) in percentages (%) in Experiment 11.

Cue position	Spatial cuing	SOA (ms)	RTs (ms)	SEs (ms)	ERs (%)
Front	Cued	100	433	6	1.9
		250	396	5	1.0
		500	383	6	3.0
	Uncued	100	448	4	2.6
		250	417	4	1.4
		500	411	7	1.7
Rear	Cued	100	440	5	1.3
		250	405	5	2.4
		500	389	5	2.4
	Uncued	100	454	5	1.8
		250	410	5	1.9
		500	400	4	4.0

5.3.2.1. RT data analysis

Three within-participants factors of Cue Position, Spatial Cuing, and SOA were entered into a RM-ANOVA. The analysis revealed a main effect of Spatial Cuing, $F(1, 17) = 22.793$, $MSE = 578.233$, $p < .001$, $\eta_p^2 = .573$, with participants responding significantly more rapidly when the cue and target were presented from the same (M = 408ms) rather

than from different sides (M = 424ms), $t(17) = -5.017$, $p < .001$. There was also a main effect of SOA, $F(1.329, 22.589) = 43.729$, $MSE = 1540.018$, $p < .001$, $\eta_p^2 = .720$, with participants responding significantly more slowly at the 100ms (M = 444ms) as compared to either the 250ms (M = 407ms), $t(17) = 11.016$, $p < .001$, or 500ms SOA (M = 396ms), $t(17) = 6.936$, $p < .001$. Such a modulation of the SOA on the RTs to targets is known as the foreperiod effect (Bertelson, 1967; Niemi & Näätänen, 1981), and is consistent with previous reports (e.g., Mazza, Turatto, Rossi, & Umiltà, 2007; Spence & Driver, 1997a). No other significant terms were documented.

5.3.2.2. ER data analysis

An equivalent RM-ANOVA on the ER data revealed a significant main effect of SOA, $F(2, 34) = 4.208$, $MSE = .001$, $p = .023$, $\eta_p^2 = .198$, with participants making more errors (although not significantly after Bonferroni correction with $\alpha = .0167$) in the 500ms SOA (M = 2.8%) than in the 100ms (M = 1.9%), $t(17) = -2.170$, $p = .044$, and 250ms (M = 1.7%), $t(17) = -2.483$, $p = .024$. No other significant terms were documented.

5.3.3. Discussion

The results of Experiment 11 confirmed the hypothesis that the presentation of a brief cue would elicit a rear-to-front crossmodal spatial cuing effect without interacting with the SOA factor. Therefore, the spatially-specific (i.e., no rear-to-front) crossmodal cuing effects reported in Experiment 10 cannot be attributable simply to the extended SOAs that were used in that study. The findings of Experiments 10 and 11, when taken together, add further support for the claim that the sound parameters can modulate the crossmodal exogenous orienting of spatial attention.

5.4. General discussion

In Experiment 5, the presentation of a brief constant-intensity auditory cue either in the pure tone or white noise structure facilitated the perception of frontal visual targets, regardless of whether the cues were presented in the front or rear (see also Experiment 2, for similar findings). However, rather unexpectedly, the presentation of a looming white noise cue with a duration of 1,000ms in Experiment 3 elicited a larger spatial cuing effect when the cues were presented in frontal space than from the rear. Such a finding suggested that looming white noise cues might be able to exogenously orient participants' crossmodal spatial attention more narrowly to the cued region of space than the brief cues traditionally used in crossmodal attention research (e.g., McDonald et al., 2003; Spence & Driver, 1997a). The results of the exogenous crossmodal cuing task reported in Experiment 10 replicated the spatially-specific cuing effect reported in Experiment 3 using looming white noise. The data from Experiment 11 confirmed that such spatially-specific cuing effects cannot simply be attributed to the extended SOAs. Taken together, the results reported in this chapter therefore suggest that the sound parameters can modulate the crossmodal exogenous orienting of spatial attention.

The data presented in this chapter confirmed the asymmetry in perceptual bias for looming sounds in preference to receding sounds from structured auditory cues in the exogenous crossmodal spatial cuing study. The presentation of a looming structured cue elicited a spatially-specific cuing effect, whereas that of a receding structured cue resulted in a rear-to-front crossmodal spatial cuing effect. The magnitude of the crossmodal spatial cuing effect in the looming structured cue condition was also significantly larger than that reported in the receding structured cue condition. With the white noise cues, the findings on the magnitude of the cuing effects were also consistent with the previous report (Ghazanfar et al., 2002; Leo et al., 2011; Neuhoff, 1998, 2001);

there was no significant difference in the magnitude of the cuing effects between the looming white noise and receding white noise cue conditions. However, the presentation of a receding white noise cue, unlike a looming white noise cue, elicited the rear-to-front crossmodal spatial cuing effect, observing the perceptual bias for looming sounds in preference to receding sounds from white noise sounds. It is also worth noting that the difference in magnitude of the crossmodal spatial cuing effect between the front and rear receding white noise cue conditions exhibited a marginal trend toward significance.

To date, the differential effect of the looming and receding sounds from structured auditory stimuli has often been interpreted as an evolutionary adaptation that increases the chance of the organisms' survival (see Ghazanfar et al., 2002; Leo et al., 2011; Neuhoff, 1998, 2001). For instance, it was argued that looming structured tones are ecologically more meaningful (e.g., potentially signalling an approaching predator), "*whereas white noise is associated with* […] *dispersed phenomena such as wind or rain*" (Maier & Ghazanfar, 2007, p. 4099). Clearly, the sound of, for example, an approaching lion provides more ecologically important information than the perception of wind or rain. Nonetheless, the presentation of a localised looming white noise cue could elicit spatially-specific cuing effects, just as well as a looming structured auditory cue. The results reported in this chapter therefore suggest that looming white noise sounds may lack the ecological meaning, but they can be as effective as (or more effective than) looming structured sounds in the crossmodal exogenous orienting of spatial attention (see McCarthy & Olsen, 2017, for similar findings).

The findings reported in this chapter may have important implications for the design of in-vehicle auditory warning signals. We often hear tonal noises (e.g., brief or extended beep noises) as warning signals presented non-spatially in a vehicle. The presentation of such a tonal warning signal may increase the alertness of a vehicle operator, and

therefore help them to respond more quickly to a certain situation. However, the findings reported in this chapter suggest that the facilitation by the alerting effect may result in increased inappropriate (i.e., error) responses. In fact, driving simulation studies also documented that non-spatial warning signals that lead to faster RTs (i.e., higher alertness; e.g., screeching tire or car horn sounds) than other types of sound (e.g., tonal or speech warnings) often also lead to greater error responses. For instance, Graham (1999) reported that the onset of a screeching tire or car horn sound from a single source location gave rise to faster RTs to impending collisions than tonal warnings. However, the participants in his study made more error responses following the onset of a screeching tyre or car horn sound than that of a tonal or speech warning (see also Gray, 2011, for similar findings). The findings reported in this chapter suggest that spatial looming or receding white noise warnings for approaching or distancing potential danger, respectively, can be effective in assisting vehicle operators to monitor the surrounding, while minimizing the onset of inappropriate responses (though see Spence & Ho, 2015, for discussion on the potential limitations of the laboratory-based study findings in the real-world application; see also Chapter 6 for further discussion).

Chapter 6. General discussion

6.1. Summary

The research that has been published to date demonstrates that the presentation of a brief auditory cue can exogenously orient people's spatial attention crossmodally to the cued region of space for approximately 300ms (Spence et al., 2004; Spence & McDonald, 2004, for reviews). The crossmodal exogenous orienting of spatial attention results in faster RTs (and often lower ERs) in response to visual targets presented in the cued region of space than elsewhere (Chapter 1; Spence et al., 2004, for a review). Such crossmodal cuing effects are known to be spatially-specific in the sense that RTs to targets are faster when the auditory cue and visual target are presented from the same, rather than different, positions (Driver & Spence, 1998; Schmitt et al., 2001). What is more, similar findings have been reported from simulated driving studies, suggesting that auditory warning signals could be presented from the direction of potential danger in order to alert vehicle operators (Ho & Spence, 2005; Ho, Spence, & Tan, 2005; Ho et al., 2006; see Ho & Spence, 2008, for a review). Over the last decade or so, interest in the design of auditory warning signals has expanded to include an evaluation of the efficacy of looming sounds in terms of their ability to reduce RTs to visual targets in simulated driving tasks (Gray, 2011; Ho et al., 2013).

Even though the simulated driving studies demonstrated that the presentation of an auditory cue in rear space facilitates the perception of rear visual targets, it is important to note that the targets were actually seen via a mirror placed in frontal space (Ho & Spence, 2005; Ho et al., 2005, 2006). Thus, such results cannot be taken to suggest that

the presentation of an auditory cue from the rear exogenously directed the visual attention to the space behind the participant's head (see Chapter 1). Furthermore, to the best of my knowledge, there is no evidence as to whether the findings of crossmodal spatial cuing effects documented in frontal space can be generalised to the rear. Given the limited evidence regarding crossmodal spatial effects involving rear space, and given the importance of answering this question for the design of warning signals, I became curious as to whether auditory cues could, in fact, also be used to alert vehicle operators about potential danger in rear space, as previously suggested. Hence, the initial question for my DPhil was, can the findings of crossmodal spatial cuing effects from studies with the stimuli presented from the frontal space be generalised to the rear space? In other words, will the presentation of a brief auditory cue from the rear orient crossmodal spatial attention narrowly to the cued region of space? The second fundamental question to be addressed by my DPhil research was, do any of the sound parameters such as cue duration, intensity, or type (e.g., pure tone vs. white noise) modulate crossmodal spatial cuing effects, and if so, how?

In order to investigate the first question for my DPhil, and to pave the way to the second question, three experiments were conducted in Chapter 2.[22] The findings of Experiment 1 replicated the crossmodal spatial cuing effect reported two decades ago by Spence and Driver (1997a), suggesting that the apparatus set-up was sensitive enough to detect such crossmodal facilitation effects. In order to test the spatial specificity of a crossmodal cuing effect, Experiment 2 was conducted using the same set-up as in Experiment 1, except for the addition of two loudspeakers placed behind the participant's head. The rear-to-front crossmodal spatial cuing effect reported in Experiment 2 challenged the

[22] I considered (naïvely) the first question as an assumption that was most-likely to be correct and needed a simple confirmation. As a result, following the discovery of the rear-to-front crossmodal spatial cuing effect in Experiment 2, the second question had to be put on hold until the answers to the first question became clear as a result of the experiments reported in Chapters 3 and 4.

generally-accepted view that exogenous crossmodal cuing effects are always highly spatially-specific. Experiment 3 was subsequently conducted in order to test whether there would be any crossmodal spatial cuing effect following the presentation of looming sounds with a duration of 1,000ms. The results of this experiment suggested that looming sounds might elicit a larger crossmodal spatial cuing effect and exogenously orient crossmodal spatial attention more narrowly to the cued region of space than brief auditory cues. Given the spatial specificity of crossmodal cuing effects reported elsewhere using brief auditory cues (e.g., Driver & Spence, 1998; Schmitt et al., 2001), I worried that the rear-to-front crossmodal spatial cuing effect documented in Experiment 2 might, for whatever reason, not be a robust empirical phenomenon.

The experiments reported in Chapter 3 were designed to further investigate the first DPhil question related to the rear-to-front crossmodal spatial cuing effect documented in Experiment 2 (Chapter 2). The set-up of the apparatus was modified in order to increase the lateral separation of the visual targets from 18.4° to 90° (see Chapter 2, for a discussion on the target eccentricity and its potential influence on the sensitivity of detecting the differential cuing effects between the front and rear cue conditions). The results of Experiment 4 replicated the spatial cuing effect reported in Spence and Driver (1997a) using the new set-up. Despite the adjusted left-right target separation, the data from Experiment 5 replicated the rear-to-front crossmodal spatial cuing effect reported previously in Experiment 2 (Chapter 2). That said, the findings from the sound location discrimination study conducted in Experiment 6 suggested that the participants did not experience front-back confusion from the auditory stimuli used in Experiment 5. The response properties of multisensory neurons in the SC were discussed in order to explain the potential mechanism for the rear-to-front crossmodal spatial cuing effects. Based on the findings of Experiments 2 and 5 reporting the rear-to-front crossmodal spatial cuing

effects and based on the neurophysiological data to support such results, I therefore began to doubt the previous reports on the spatial specificity of crossmodal cuing effects.

The three experiments reported in Chapter 4 were conducted in order to try and replicate the within-hemifield crossmodal spatial cuing effects (Driver & Spence, 1998; see also Schmitt et al., 2001), and to confirm the spatial specificity of crossmodal cuing effects in frontal space. All three experiments reported that RTs to targets were faster when the cue and target stimuli were presented from the same position than from different positions within the cued hemifield, following the onset of the cue from the inner eccentricity. When the auditory cues were presented from the outer eccentricity, however, the data from all three experiments failed to document such within-hemifield crossmodal spatial cuing effects. Furthermore, the results of all three experiments demonstrated the eccentricity effect: RTs to visual targets presented from the inner eccentricity were significantly faster than those from the outer eccentricity (see Carrasco et al., 1995; Carrasco & Frieder, 1997, for similar findings). Therefore, the eccentricity effect was pointed out as a potential modulator for the lack of within-hemifield crossmodal spatial cuing effects when the cues were presented from the outer locations. The response properties of multisensory neurons in the SC were discussed in order to try and explain the findings of the within-hemifield spatial cuing effects (or the lack thereof). The further analyses of the RT data without the eccentricity confound suggested that the presentation of an auditory cue exogenously oriented crossmodal spatial attention narrowly to the cued region of space within the cued hemifield. However, it became clear that crossmodal cuing effects were not spatially-specific in a way that some researchers have had led us to believe.

Unexpectedly, the traditional view concerning the spatial specificity of crossmodal cuing effects held true when looming auditory cues were used in Experiment 3 (Chapter 2).

Experiment 10 (Chapter 5) was conducted in order to further investigate how sound parameters such as cue duration, intensity change, and waveform structure would modulate the exogenous crossmodal spatial attention (i.e., my second DPhil question). The findings revealed that the presentation of a looming (either structured or white noise) auditory cue could elicit spatially-specific crossmodal cuing effects. Furthermore, the magnitude of the crossmodal spatial cuing effect was larger from looming structured than receding structured cues, thus confirming the perceptual bias for looming sounds in preference to receding sounds in the structured auditory cue condition. No such perceptual bias for looming sounds in preference to receding sounds was found in the white noise cue condition (see Ghazanfar et al., 2002; Leo et al., 2011; Neuhoff, 1998, 2001, for similar findings). Therefore, the data from Experiment 10 provided the first evidence in support of the perceptual bias for looming sounds in a crossmodal spatial cuing study. Such findings cannot be attributed to the extended SOA (see Experiment 11 in Chapter 5; see also Experiments 2 & 5 in Chapters 2 & 3, respectively). See Table 6.1 for the summary of stimuli, design, and results of all the experiments reported in this thesis.

Table 6.1.

Summary of the stimuli, designs, and key findings from each experiment (E).

Experiment		Stimuli	Designs	Key findings
Chapter 2	E1	50ms white noise auditory cues & white circle visual targets	Spatial Cuing (cued vs. uncued) x SOA (100, 200, 400, or 700ms)	Spatial cuing effect
	E2	Same as E1	Cue Position (front vs. rear) x Spatial Cuing x SOA	Rear-to-front crossmodal spatial cuing effect
	E3	1,000ms white noise looming or constant-intensity auditory cue & white circle visual targets	Cue Position x Cue Type (looming vs. constant-intensity) x Spatial Cuing x ISI (50, 150, or 400ms)	Spatially-specific crossmodal cuing effect in the looming cue condition No spatial cuing effect in the constant-intensity cue condition
Chapter 3	E4	100ms pure tone or white noise cues & LED visual targets	Cue Type (pure tone vs. white noise) x Spatial Cuing x SOA (100, 200, or 700ms)	Same as E1
	E5	Same as E4	Cue Position x Cue Type x Spatial Cuing x SOA	Same as E2
	E6	100ms pure tone or white noise targets (i.e., no visual targets)	Target Position (front vs. rear) x Target Type (pure tone vs. white noise)	No front-back confusion
Chapter 4	E7	100ms white noise cues & LED visual targets separated by 30° laterally and by 69° vertically	Cue Location (outer-left, inner-left, inner-right, outer-right) x Target Location (outer-left, inner-left, inner-right, outer-right)	Within-hemifield crossmodal spatial cuing effect only when the cues were presented from the inner eccentricity Eccentricity effect
	E8	Stimuli same as in E7 except LED visual targets separated by 30° laterally and by 38° vertically. Designs and key findings same as E7		
	E9	Stimuli same as in E7 except LED visual targets separated by 10° laterally and by 8° vertically. Designs and key findings same as E7.		
Chapter 5	E10	250ms or 500ms auditory cues & LED visual targets	Cue Position x Cue Type (looming vs. receding) x Cue Structure (structured vs. white noise) x Spatial Cuing x Cue Duration (250 vs. 500ms)	Spatially-specific cuing effects in the looming structured and looming white noise cue conditions Larger cuing effects from looming than from receding cues
	E11	110ms white noise & visual targets same as E10	Cue Position x SOA (100, 250, or 500ms) x Spatial Cuing	Rear-to-front cuing effects, regardless of the SOA

6.2. Study limitations and further discussion

6.2.1. Limitations in the study designs

The visual targets used for the experiments reported in Chapter 2 were separated laterally by 18.4°, potentially responsible for the small spatial cuing effects documented in Experiments 1 and 2 (i.e., 5ms). Furthermore, the perceived duration of the looming cue could be different from that of the constant-intensity cue, because the intensity of the former was 0dBA at its onset. The target eccentricity issue was addressed in Chapter 3, by widening the lateral separation between the left and right targets by 90°. The perceived duration issue with the looming auditory cues in Experiment 3 was resolved in Experiment 10 (Chapter 5) by varying the cue intensities between 55 and 75dBA.

The results of the sound location discrimination task (see Experiment 6 in Chapter 3) were taken to suggest that the rear-to-front crossmodal spatial cuing effect reported in Experiment 5 could not be attributable to front-back confusion. However, it is worth noting that the sound location discrimination task was conducted separately from the spatial cuing task. Therefore, the participants in Experiment 5 might have experienced some sort of front-back confusion *while* engaged in the visual target elevation discrimination task. One might suggest the inclusion of randomly-placed sound location discrimination trials in-between the spatial cuing trials, in order to investigate whether the participants would be able to correctly discriminate the location of auditory cues. However, the sound location discrimination trials, if included between spatial cuing trials, would lead the participants to pay more attention to the location of auditory cues, and potentially bias the data from the exogenous crossmodal spatial cuing task (i.e., the location of auditory cues would no longer be task-irrelevant). Therefore, the possibility of front-back confusion cannot be completely ruled out for the documented rear-to-front

crossmodal spatial cuing effects in Experiments 2, 5, and 11 (in Chapters 2, 3, & 5, respectively).

Although durations (250 vs. 500ms) of the auditory cues did not interact with the spatial cuing conditions in Experiment 10, it is worth noting that both cue durations were considerably longer than the brief cues that have been used elsewhere (McDonald et al., 2003; Spence & Driver, 1997a; see also Chapters 2 & 3). Therefore, it is unclear how long (or short) the duration of a looming cue can be so that its presentation would elicit the perceptual bias and eliminate rear-to-front crossmodal spatial cuing effects as documented in Experiment 10. If I were to conduct the experiment again, I would want to investigate the minimum duration of a looming cue that is needed in order to observe the perceptual bias and the spatially-specific cuing effect, using the cue durations of 50, 100, 150, and 200ms.

6.2.2. Limited generalisability of the neurophysiological explanations

The rear-to-front crossmodal spatial cuing effects (Experiments 2 & 5 in Chapters 2 & 3, respectively) and the within-hemifield spatial cuing effects documented only when the cues were presented from the inner eccentricity (Experiments 7-9 in Chapter 4) challenge previous reports on the spatial specificity of crossmodal cuing effects (Driver & Spence, 1998; Schmitt et al., 2001; see Spence & McDonald, 2004, for a review). The response properties of the multisensory neurons in the deep layers of the SC were suggested as one of the potential mechanisms for the rear-to-front and the within-hemifield exogenous crossmodal spatial cuing effects. That said, the neurophysiological data from the SC

alone cannot account for the modulation of sound parameters on the crossmodal spatial cuing effects (Experiment 10 in Chapter 5; see also Experiment 3 in Chapter 2).

Perhaps, the perceptual bias towards looming sounds in preference to receding sounds could be the result of cortical inputs to the SC, since the latter structure receives descending projections from auditory cortex (Chabot et al., 2013; Lomber, Malhotra, & Hall, 2007; see also Paula-Barbosa & Sousa-Pinto, 1973; Tortelly et al., 1980). Indeed, it has been shown that looming sounds, compared to receding sounds, activate various cortical regions involved in the perception of auditory space and attention, such as superior temporal sulcus (STS) and the middle temporal gyrus (MTG; Seifritz et al., 2002; see also Maier & Ghazanfar, 2007). It is possible that those cortical regions project inhibitory signals for receding sounds to the SC via anterior ectosylvian sulcus (AES), which is identified as a potential gateway for signals concerning sound localisation from the auditory cortex to the SC (Lomber et al., 2007; see also Chabot et al., 2013; Paula-Barbosa & Sousa-Pinto, 1973; Tortelly et al., 1980).

Furthermore, the lack of rear-to-front crossmodal spatial cuing effects from the looming sounds that was reported in Experiment 10 might be attributable to the interaction between the perceptual bias towards the looming sounds and the spectral cues provided by the extended cue duration. In fact, the spectral cues, generated by the external ear (pinna; see Butler, 1975, for a review) as well as the head and torso (Algazi, Avendano, & Duda, 2001), are regarded as providing some of the most salient information concerning sound localisation (see Wightman & Kistler, 1997). Spectral cues are crucial for sound localisation on the vertical plane and resolving front-back ambiguity (Ovcharenko et al., 2007; Slattery & Middlebrooks, 1994; Talagala, Zhang, Abhayapala, & Kamineni, 2014; Wenzel, Arruda, Kistler, & Wightman, 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 location of the sound source changes (Mehrgardt & Mellert, 1977; Musicant, Chan, & Hind, 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 below 3kHz (Algazi et al., 2001). Spectral cues between 4-16kHz are essential for sound localisation 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, Suzuki, & Sone, 1990; see also Musicant & Butler, 1984). Two of the most important brain regions processing spectral cues are the IC (Davis et al., 2003; see also Davis, 2005, for a review) and the auditory cortex (Zatorre & Belin, 2001; see Schreiner, Froemke, & Atencio, 2011, for a review).

The IC, situated under the SC, constitutes one of the major brain regions relaying auditory information to the SC (García Del Cãno, Gerrikagoitia, Alonso-Cabria, & Martínez-Millán, 2006), and processes spectro-temporal information (Wenstrup, Nataraj, & Sanchez, 2012). Therefore, when an auditory cue is presented briefly (i.e., for 100ms or less; Experiments 2 & 5 in Chapters 2 & 3, respectively), the spectro-temporal integration in the IC may not have been complete (cf. Hofman & Van Opstal, 1998). However, following the presentation of an auditory cue for 250ms or more in rear space, the IC inputs may contain more accurate information regarding the spatial location of the cue compared to those from the brief cues. Such spectro-temporal information from the IC inputs could then lead to response inhibition in the SC for those multisensory neurons with the auditory RFs extending to the rear space, potentially eliminating the rear-to-

front crossmodal spatial cuing effect. In order to test whether the IC inputs play a role in eliminating the rear-to-front crossmodal spatial cuing effects, future studies would want to first identify SC multisensory neurons that integrate a rear auditory cue and a frontal visual target. Second, investigate whether such multisensory integrations become inhibited over time from the exposure of, for instance, a looming white noise cue presented from the rear and a visual target in the front. Third, once the extended exposure of the audiovisual stimuli is confirmed to result in the inhibition of multisensory integration, deactivate the IC, repeat the second procedure, and observe whether the same inhibition of multisensory integration occurs.

6.2.3. Potential limitations due to the laboratory settings

In a typical laboratory-based spatial cuing study, participants respond to hundreds of targets in less than an hour. However, vehicle operators do not encounter potential danger on the road anything like as frequently. Therefore, it is unclear whether and to what extent the findings reported in this thesis can be generalised to those circumstances in which auditory warning signals in response to potential road danger appear less frequently than a typical laboratory setting. Should the findings reported here be considered in the design of auditory warning sounds for vehicle operators, it is important to investigate whether the results can be replicated when auditory warnings and potential dangers are expected far more infrequently (see Spence & Ho, 2015, for a review).

Another constraint on the findings reported in this thesis is that the repetitive procedure of each trial might have led the participants to pay attention to the auditory cues unintentionally. The fixation stimulus, a cue, an SOA/ISI, and a target were all presented in that same order. Therefore, the onset sequence of the fixation and an auditory cue could have functioned as a countdown for the onset of a visual target. In that sense, the

auditory cues in the spatial cuing tasks were not completely task-irrelevant, at least not in the temporal dimension, even though they were irrelevant to the location of the targets. Therefore, it is possible that the data concerning the putatively 'exogenous' orienting of crossmodal spatial attention reported in this thesis might reflect a mixture of both endogenous and exogenous spatial orienting (although see Santangelo & Spence, 2008; Spence, 2010; Spence & Santangelo, 2010, for further discussion that exogenous orienting is, in fact, only partially-automatic).

Lastly, it should be noted that all of the experiments reported in this thesis were all conducted in the University of Oxford. Even though the participants recruited for the experiments reported in this thesis included some of those who were not university students or staff, most of them were associated with the University of Oxford (e.g., University alumni, visiting scholars, etc.). As a result, the findings reported in this thesis are based on the members of the WEIRD (Western, educated, industrialised, rich, & democratic; Henrich, Heine, & Norenzayan, 2010) population, and may not generalise to other demographics. It would be interesting to see whether and to what extent the evidence in support of crossmodal spatial cuing effects can be replicated with, for instance, non-Western participants. It should be also pointed out that the average age of the participants was below 30 years. Therefore, it would be also worth investigating whether there is any potential difference in the patterns of crossmodal spatial cuing effects between young and old age groups (Spence & Ho, 2015).

6.3. Implications and future directions

To date, evidence in support of the existence of exogenous crossmodal spatial cuing effects is mostly based on the studies using stimuli in the narrow frontal space, which has

largely been divided into the left and right hemifields (Chapter 1). Yet, it has been generally accepted that the cuing effects measured in RTs to targets are spatially-specific (i.e., fastest when the cue and target are presented from the same position; see Spence et al., 2004; Spence & McDonald, 2004). The findings reported in this thesis suggest that the current understanding of exogenous spatial attention is limited to the frontal space (Chapters 2 & 3; see also Van der Stoep et al., 2015b; Van der Stoep, Serino, Farnè, Di Luca, & Spence, 2016, for reviews on the limited spatial scope of current crossmodal research data), to certain experimental settings (e.g., the eccentricity of the cue and target; Chapter 4), and to the use of brief constant-intensity auditory cues (Chapter 5). Based on the findings reported in this thesis, future research would want to pay more attention to the rear space, and to the role of sound parameters in the crossmodal exogenous orienting of spatial attention. The challenge would be to develop a coherent theory/model that can consolidate the findings available today based on the studies using traditional auditory stimuli presented in the frontal space, and those to be discovered in such future research.

The findings reported in this thesis as well as those to be discovered in the future research proposed above may be able to provide crucial information with regard to the design of auditory warning signals for drivers. Of course, some might doubt the long-term benefit of the further investigation in spatial cuing research for the design of in-vehicle warning signals, due to the rapid development in self-driving cars (e.g., "All Tesla," n.d.; "Google Self-Driving," n.d.). However, it has been argued that the public may not yet be ready to give up the control to the self-driving technology (see Spence, 2012; also see Ferris, 2017; Gareffa, 2017). Moreover, extensively-publicized recent accidents caused by self-driving system failures (see Boudette & Vlasic, 2017; Lee, 2016; Levin & Woolf, 2016; also see Hern, 2016) suggest that it might take a while for

the public, not to mention the legal system (Greenblatt, 2016), to fully embrace the consequences of self-driving cars. Until such a time, improving collision warning systems that can compensate for driver inattention remains a crucial task for both applied and laboratory attention researchers working in the field of ergonomics (Spence, 2012).

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