

Related but different: Examining pseudoneglect in audition, touch and vision

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Although researchers have consistently demonstrated a leftward attentional bias in visual and representational (e.g. tactile/mental number line) line bisection tasks, the results from audition have been mixed. Differences in methodology have also meant that researchers have not been able to compare directly performance in visual, tactile and auditory line bisection. In this research, 39 neurologically typical individuals participated in standard visual and tactile line bisection tasks, together with a newly developed auditory line bisection task. Results demonstrated significant leftward bisection biases across all three modalities. Hence, we demonstrate auditory pseudoneglect in peripersonal space for the first time. Tactile and auditory line bisections showed a relatively small but statistically reliable correlation, but neither task correlated with visual line bisection. This suggests that the processes underlying auditory line bisection are not synonymous to those involved in visual perceptual bisection, and further we argue that this bias may be related to representational pseudoneglect.

1.1 Introduction

When asked to mark the midpoint of a series of lines printed on a sheet of paper, research has shown that neurologically typical individuals demonstrate a small but consistent tendency to mark to the left of the veridical midpoint (Kinsbourne, 1970, Jewell & McCourt, 2000). This bisection bias has been labelled “pseudoneglect” (Bowers & Heilman, 1980). It mirrors a clinical condition called hemispacial neglect, or contralesional neglect. This condition manifests as a lateralised disruption of spatial attention, where there is a deficit in attention to one side of space following damage to the contralateral hemisphere. The evidence that severe neglect is associated with right hemisphere lesions (Mesulam, 1999), led researchers to conclude that visual spatial attention is lateralised in the right parietal cortex (see Kerkhoff & Lebel., 2006). Brain imaging studies examining the neural basis of pseudoneglect also indicate a role of the right hemisphere, by demonstrating enhanced right hemisphere activation in visuospatial and line bisection tasks (e.g. Fink, Marshall, Shah, Weiss, Halligan, Grosse-Ruyken, Ziemons, Zilles, & Freund, 2000). Further, evidence from TMS and theta burst stimulation has demonstrated a causal relationship for areas within the right parietal cortex but not the primary visual cortex in pseudoneglect tasks (Bjoertomt, Cowey & Walsh, 2002; Varnava, Dervinis, & Chambers, 2013). Consistent with this, pseudoneglect has been explained with reference to hemispheric dominance patterns in spatial processing (Heilman & Van Den Abell, 1979; Reuter-Lorenz, Kinsbourne & Moscovitch, 1990; Brooks et al, 2014). Benwell, Harvey and Thut (2014) specifically implicate ventral attentional networks in the right hemisphere with pseudoneglect. Their research is consistent with De Schotten, Dell'Acqua, Forkel, Simmons, Vergani, Murphy, & Catani, (2011), who showed a strong positive correlation between the size of the right hemisphere middle superior longitudinal fasciculus (a fronto-parietal white matter tract) and leftward line bisection error. They suggested that lateral asymmetries related to perceptual biases may be reflected in network connectivity as well as patterns of activation (De Schotten et al., 2011).

Clinical presentation of neglect has been associated with deficits in attention across sensory modalities, global-local processing, spatial memory and mental representation (see Halligan, Fink, Marshall & Valler, 2003; Bisiach & Luzzatti, 1978; Beschin, Cocchini, Della Sala, & Logie, 1997). This has raised questions about whether similar visuospatial perceptual or attentional mechanisms are involved in all of these tasks, or if these tasks are simply located in spatially proximal brain areas, but rely on distinct cognitive mechanisms. A series of studies by Beschin, Della Sala, Denis and Logie have explored a related issue – whether pure

perceptual neglect and pure representational neglect make use of identical cognitive mechanisms. Their findings demonstrate double dissociations between pure perceptual neglect (neglect of items on the left of a visually presented array) and pure representational neglect (neglect of items on the 'left' of a verbally described array) (Denis, Logie, Beschin & Della Sala, 2002, see also: Beschin, Basso & Della Sala, 2000; Bartolomeo, D' Erme, & Gainotti, 1994; Cantagallo & Della Sala, 1998; Coslett, 1997; Beschin, et al., 1997; Guariglia, Padovani, Pantano, & Pizzamiglio, 1993; Ortigue, Viaud-Delmon, Anoni, Landis, Michel, Blanke, Vuilleumier & Mayer, 2001). There is evidence that this type of distortion to representation affects the representational system itself but not the mechanism by which representations might be manipulated – mental rotation processes seem to preserve the integrity of the initial representations rather than degrade them further (Logie, Della Sala, Beschin, Denis, 2005; Della Sala, Logie, Beschin, Denis, 2004). It is also the case that dissociations in the type of material that is affected within representational neglect exist (Ortigue, Viaud-Delmon, Michel, Blanke, Annoni, Pegna, Mayer, Spinelli, and Landis, 2003). Piccardi, Bianchini, Zompanti & Guariglia (2008) reported a patient who showed a pure representational neglect in navigational situations and in reporting familiar landmarks (one of the classic tests of representational neglect: Bisiach & Luzatti, 1978) but who showed no deficit on the Corsi Block Tapping task of spatial working memory (Corsi, 1972).

In line with performance on perceptual tasks, neurologically typical individuals also show a leftward lateral bias in tasks based on mental representation. Such tasks include the bisection of mental number lines and mental representations of visuospatial information (e.g. Beschin et al., 1997; Longo and Lourenco, 2006; Zorzi, Priftis and Umiltà, 2002; Nicholls & Loftus, 2007). Where these leftward biases are observed for stimuli that are represented mentally, rather than perceived within the physical world, these have been named 'representational pseudoneglect' (McGeorge, Beschin, Colnaghi, Rusconi, & Della Sala, 2007). Researchers have shown that performance for physical and mental number line bisection can correlate within individuals (Longo & Lourenco, 2007). Further, evidence from TMS has supported that similar brain areas are activated in both tasks (Cattaneo, Silvanto, Pascual-Leone, & Battelli, 2009; Gobel, Calabria, Farne, & Rossetti, 2006; Oliveri, Rausei, Koch, Torriero, Turriziani, & Caltigrone, 2004).

Given the commonalities in behaviour and the neural mechanisms underlying representational pseudoneglect, researchers initially concluded that the processes underpinning visuospatial attentional processing also underpinned mental representation (e.g. Longo & Lourenco, 2007). However, in line with findings in clinical neglect, evidence of dissociations between visuospatial pseudoneglect and representational pseudoneglect cast doubt on these early conclusions. For example, Darling, Della Sala and Logie (2012) showed that whilst bisecting visual lines presented in extrapersonal space did not result in pseudoneglect (see also Longo and Lourenco, 2010; Gamberini, Seraglia, & Priftis, 2008; Longo & Lourenco, 2006, 2007; Lourenco & Longo, 2009; Varnava, McCarthy & Beaumont, 2002), pseudoneglect was observed for *remembered* lines presented in extrapersonal space. Further, whilst congenitally deaf individuals did not demonstrate the standard visual line bisection bias for perceptually perceived visual lines (Cattaneo, Lega, Cecchetto & Papagno, 2014), they did demonstrate leftward pseudoneglect in a mental number line task (Cattaneo, Cecchetto, & Papagno, 2015). As such, despite there being some underlying similarities, there is a case to suggest that representational and visual-perceptual pseudoneglect might be mediated by distinct mechanisms.

Neurotypical individuals also tend to display a similar leftward bias in tactile tasks (Jewell & McCourt, 2000). Performance on tactile line bisection tasks is affected by many of the same factors that impact on visual line bisection tasks (Cattaneo, Fantino, Tinti, Silvanto and Vecchi., 2010; Bowers & Heilman, 1980; Hach & Schutz-Bosbach, 2012; Brodie & Pettigrew, 1995; Brooks, Della Sala & Logie 2011). Nevertheless, there are noticeable differences, for example overshooting/undershooting the line midpoint (Brooks et al, 2011; Brooks, Della Sala & Darling, 2014; Baek, Lee, Kwon, Park, Kang, Chin, Heilman, & Na et al., 2002; Brodie & Dunn, 2005; Brodie & Pettigrew, 1996). One key point of difference between tactile and visual bisection is that the tactile perceptual field is perceived sequentially, and a representation of the stimulus needs to be built up using manual motor exploration (Gentaz, Baud-Bovy, & Luyat, 2008). Consequently, Brooks et al., (2014) suggest that tactile pseudoneglect is reliant on the individual generating a mental representation of the line length, derived from the tactile and proprioceptive information gathered as the finger moves from one end of the line to the other. Hence tactile line bisection is argued to be an example of representational pseudoneglect. This is supported by evidence that visual and tactile hemispatial neglect are not always co-morbid within the same

individual (e.g. Barbieri & De Renzi, 1989) and also that tactile and visual bisection do not seem to correlate strongly in neurotypicals (Rueckert, Deravanesian, Baboorian, Lacalamita & Replinger, 2002; Brooks, Darling, Malvaso, Della Sala, 2016).

Thus far, it seems reasonable to suppose that pseudoneglect can be usefully viewed as potentially classifiable into perceptual and representational elements, though actual tasks may incorporate varying mixtures of perceptual and representational elements. Tasks that are frequently used to assess pseudoneglect in the visual modality, such as landmark tasks (Milner, Harvey, Roberts & Forster, 1993), greyscales tasks (Mattingley, Berberovic, Corben, Slavin, Nicholls & Bradshaw, 2004) are largely perceptual in nature as the display directly affords the stimuli to be bisected or judged. In such tasks, the array is presented in its entirety and midline judgements can be made based on direct perceptual input, though perception of these displays may require multiple saccades. Any bias observed on visual trials could potentially be a consequence of a bias in immediate perception. On the other hand, tactile and mental number line bisection tasks cannot be afforded instantly due to the sequential nature of presentation (auditory presentation of mental number lines or the need to explore sequentially a tactile stimulus). Thus, these latter tasks are more reliant on the ability to build a spatial representation and keep it active over time. Under the proposed classification, it is not the particular modality of presentation that drives different patterns of pseudoneglect in different tasks, but rather, it is the extent to which the specific task used relies on participants building up mental representations. From this point of view, the degree to which perceptual factors or representational factors are evoked by visual line bisection is a little unclear as a temporally extended spatial representation may be invoked by the requirement to produce a motor response to the mid-point in the line. Accepting this proposed classification of pseudoneglect is premature because little is understood about the nature of underlying representations in tasks that require them, or about their degree of modality-specificity. One way of advancing understanding on this issue is to investigate pseudoneglect biases in auditory spatial location.

Research on auditory pseudoneglect is considerably rarer than either tactile or visual. Where research has been carried out, methodologies have been varied and difficult to compare to visual or tactile line bisection tasks. Ocklenburg, Hirnstein, Hausmann & Lewald (2010) used a method of adjustment task (where a participant attempts to directly or indirectly identify the middle of an interval by using a manual response - see Jewel & McCourt, 2000 for a full discussion of response methods in pseudoneglect tasks). However, participants were not

actually required to imagine an auditory line; rather they simply had to try to locate a single sound. They found that right- and left-handers tended to locate the sound in the space contralateral to handedness, i.e. dextrals pointed to the left of the sound source and sinistrals to the right (see also Corral & Escera, 2008). Sosa, Teder-Sälejärvi and McCourt (2010) created a forced-choice line bisection task. Sosa et al (2010) found, like Dufour, Touzalin and Candas (2007), that the bias in judgement of auditory space was significantly rightward of the midpoint. They also found a significant positive correlation in the magnitude of the bisection bias between auditory (rightward bias) and visual (leftward bias) bisections, from which they inferred interhemispheric inhibition for both modalities. However, they concluded that dissociation in the direction of bias between audition and vision implied that audiospatial and visuospatial attention are modality specific. Gori, Sandini, Martinoli & Burr (2014) explored a forced-choice form of auditory line bisection in blind individuals, and suggested that they had difficulty carrying out the task, leading them to conclude that auditory spatial attention was dependent on visuospatial processing. However, 4 of the 9 participants used by Gori et al., (2014) had lost sight due to retinopathy of prematurity, which has been associated with poorer spatial performance as compared to other early and congenitally blind individuals (Eardley, Edwards, Maloin & Kennedy, 2016). Of the other research described above, Ocklenburg et al. (2010), Sosa et al., (2010), Dufour et al., (2007) and Gori et al., (2014) all carried out line bisection in extrapersonal space (beyond arms reach). The body of research showing that the leftward bisection bias is reduced or reversed in far space (McCourt & Garlinghouse, 2000; Bjoertomt et al., 2002; Longo & Lourenco, 2010; Gamberini et al., 2008; Longo & Lourenco, 2006, 2007; Lourenco & Longo, 2009; Varnava et al., 2002) draws into question the comparability of auditory results using extrapersonal stimuli with standard peripersonal tactile and visual line bisection tasks. Consequently, there remains considerable debate about whether leftward *auditory* pseudoneglect is underpinned by a supramodal system (e.g. Ocklenburg et al., 2010), by spatial attention (e.g. Gori et al., 2014), or even if it exists at all in the auditory system (e.g. Sosa et al., 2010).

It is worth noting that although hemispacial neglect has been identified in both touch and audition, auditory lateral biases are generally not as severe as in the visual domain (see Gainotti, 2010; Soroker, Calamaro and Myslobodsky, 1995). Many patients with visual neglect do not display auditory neglect (Heilman & Valenstein, 1972; Sinnet, Juncadella, Rafal, Azanon & Soto-Faraco, 2007). Overall, auditory neglect is less frequently observed than visual neglect, and shows a more mixed pattern of lateralisation, which might relate to

the nature of acoustic wave propagation and the neural apparatus used to transmit sound to the cortical regions (Deouell, Bentin and Soroker, 2000). Nevertheless, auditory neglect clearly does exist, which suggests that auditory pseudoneglect should exist. Furthermore, studies examining the relationship between the systematic directional errors found in auditory and visual neglect have found a significant correlation between the two conditions (see Clarke & Thiran, 2004 for a review), which might suggest shared mechanisms underpin the phenomenon in both modalities.

So far, no comparison of performance in neurologically intact participants on line bisection tasks across auditory, tactile and visual stimuli has been conducted. Direct comparison of results across modalities is hampered by differences in methodology (Gainotti, 2010). The majority of research in touch and in bisection of mental representations (e.g. Longo & Lourenco, 2007) have made use of tasks that can be considered to be based on methods of adjustment. It may be that method of adjustment tasks may invoke more representational processing than forced choice tasks, given the requirement to produce an absolute versus a categorical response. The aims of the present research were threefold. First, to employ a method of adjustment paradigm in audition that was analogous to those used in vision and touch, with all tasks carried out within peripersonal space (i.e. 'within the distance at which an object can be reached by the subject's hand without moving his/her trunk': Cardinali, Brozzoli & Farnè, 2009). Second, to determine if there was a clear deviation from centre in an auditory line bisection task and the overall direction of this bias. The third aim was to extend findings from brain-damaged individuals and neuroimaging studies by providing the first within participant comparison of behavioural performance across auditory, tactile and visual modalities in neurologically typical individuals.

This research examined pseudoneglect across audition, touch and vision, and in addition investigated whether there were notable differences between or relationships in bias across modalities. Based on both the neuropsychological evidence on hemispatial neglect, as well as limited evidence of differences between perceptual and representational pseudoneglect, it seems unlikely that attentional control operates using a truly supramodal representation, which would be evidenced by not only deviations in the same direction, but strong correlations between performance across all three modalities. Instead it seems likely that there may be some similar and some independent processes. If this is the case, the precise

pattern of these relationships should tell us something about the relative importance of amodal vs. modality specific processes to pseudoneglect.

2. Methods

2.1. Participants

44 right-handed participants were recruited by opportunity sampling (female = 30). Of these, 5 were excluded for: making more than one mark on tactile/visual tasks, dyslexia, or being ambidextrous (based on Edinburgh Handedness Inventory (Oldfield, 1971)). The remaining 39 participants (25 female) were all classified as right handed by the EHI (mean score of +85.5, S.D. 17.6). The mean age of participants was 30.7 years (SD 8.4 years). One participant refused to give their age, but confirmed that they were under 50. This study was conducted following BPS ethical guidelines, and in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). Ethical approval was granted by the Psychology Department Ethics committee, University of Westminster

2.2. Materials and Equipment

Participants were tested in an acoustically treated room. The walls (but not ceiling, or floor) were sound proofed. The walls and door were covered in Adhesive PUR Foam Soundproofing Sheet (50mm thick, typical sound attenuation of -25dB(A)). All tasks were carried out within peripersonal space. In line with Longo & Lourenco (2009), this was defined as within 600mms of the individual.

2.2.1. Auditory Line Bisection

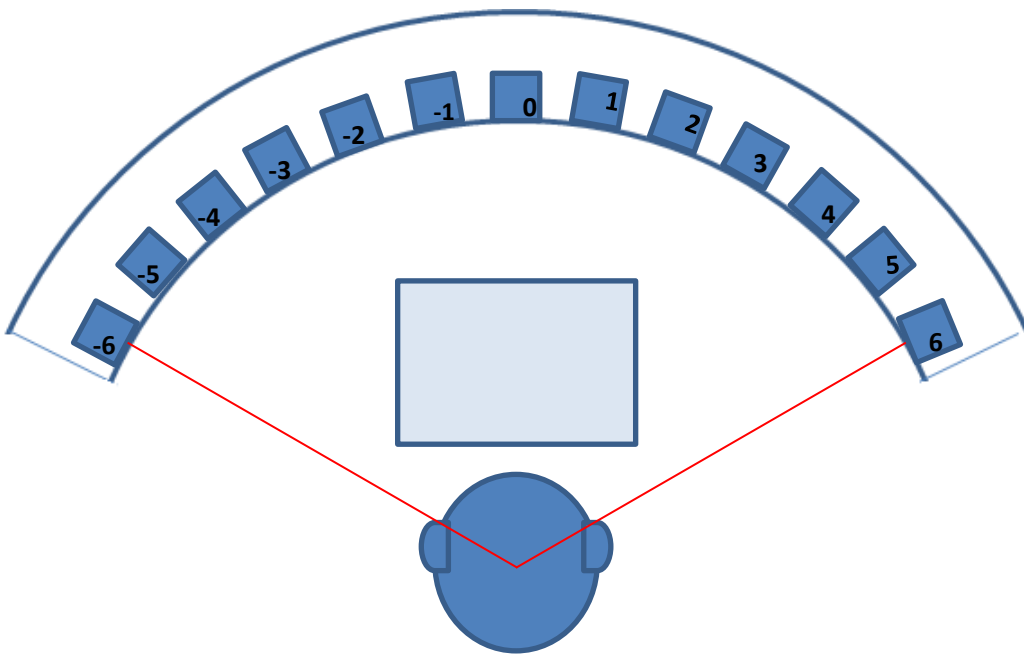
Participants placed their chin in a chin rest positioned in the middle of a foam covered table. The chin was placed inside a moulded plastic rest, the height of which was adjusted to ensure participants were sitting up-right, facing forward. The central speaker was positioned 570mm

from the base of the chin rest (approximately 70cm from the crown of the head). In total, 13 speakers were positioned in an arc, maintaining the same distance from the crown of the head. Speakers to the left of the central speaker were numbered -6 to -1. Speakers to the right of the central speaker were labelled 1 – 6 (see figure 1). The two most lateralised speakers were -6 and 6, and these were positioned at a 60° visual angle from the centre. Each speaker was positioned 9.5 cm away from the previous speaker. The speakers were custom made by Heijo Electronics and were a cut-off cuboid shape, 6.5cm wide, with the speaker cone pointing upwards at a 45° angle. Speakers were stuck to a 1inch thick piece of foam. Speaker volume was calibrated, using an A-weighted SPL meter, to within 0.5dB of each other. During the experiment, speakers were covered with an acoustically transparent fabric to prevent use of visual information to locate the sound source. The sound used was pink noise (PN) (Everest, 2001). Bursts of pink noise were 350ms in duration. These were played sequentially through the two speaker locations, with an inter-stimulus delay of 100ms. Sounds were played asynchronously in order to eliminate phasing which occurs when two audio sources are played simultaneously; the two sounds combine, creating constructive and destructive interference of the waveform. In other words, parts of the frequency band would sound louder and other parts would be quieter, making the stimuli difficult to perceive. The alternating pattern was repeated until the participant responded or for a maximum of 4 seconds. Speakers were attached to a stimulus controlling interface (Heijo electronics) between the parallel port and the speakers.

Figure 1 about here

In order to record the location of the point, a motion capture system was built in house consisting of a high resolution infra-red camera looking down onto the testing area and a small battery powered infra-red light emitting diode (LED) to mark location. The location of the LED in the scene was computed by applying a threshold just below the maximum value of illumination to isolate pixels at the point of interest, the coordinates of this pixel group were then averaged to give the location of the LED resulting in an angular resolution of better than 5 arc minutes. Calibration of each speaker position was performed with the same LED unit placed on top of each speaker in term and the position digitised. The centre on the crown of the participants head was digitised in a similar way and the LED attached facing upwards to the participants hand. During testing the position of the LED marker was digitised and logged synchronously with stimulus presentation at a frame rate of 30 fps (motion sampled at 30 Hz) together with participant button presses on a hand held response button held in the

Figure 1:



non-dominant hand. The participant was instructed to press this button once they were happy that the direction they were pointing indicated the midpoint of the stimulus. Offline analysis software was written to process the location data of stimuli with respect to calibration points. This consisted of computing the median pointing position during a window of 1 second following participant button presses and using simple trigonometry to compute the angle between left, right and pointing position relative to the crown of head calibration point. The angles were then translated into a proportional deviation from the midpoint, so that the left stimulus position took a value -1 and the right hand stimulus position took a value of +1, thus the midpoint would take a value of 0.

An E-prime programme controlled stimulus presentation. Auditory ‘lines’ were defined based on the distance between the two end points of the lines. Two auditory ‘line’ lengths were used, either a 7 speaker or a 9 speaker distance. These line lengths were centred over three different locations, the central speaker, speaker position -2 (to the left) and 2 (to the right). There were 36 trials, divided into 6 blocks, 3 per hand. The response hand used was counterbalanced within participants. The order of line presentation was counterbalanced across participants.

2.2.2. Visual Line Bisection

Two A4 sheets with 17 lines on each (total lines = 34), ranging in length between 9.45cm and 24.8cm comprised of one set of the Visual Line Bisection task. Participants completed one set for the left-hand and one for the right-hand (e.g. Hausmann, Ergun, Yazgan & Gunturkun, 2002; Patston, Corballis, Hogg & Tippett, 2006). Five lines were aligned to the left of the paper, five to the right of the paper, and seven in the centre. Lines were printed in landscape orientation. The sheets were positioned in front of the participants’ midline. Approximate viewing distance was 450mm.

2.2.3. Tactile Line Bisection

The same line lengths used for the visual line bisection task (e.g. Hausmann et al., 2002; Patston et al., 2006) were transformed into 2 ½ dimension raised line drawings using ZyTek2 swell paper. As with the VLB task, there were two sheets each for the left and right hands, with 17 lines in total for each hand (Hausmann et al., 2002; Patston et al., 2006). Lines were distributed spatially between left, right and central positions. A blindfold obscured participants' vision. A drawing pin with a plastic head was used by the participants to mark the perceived centres of the lines. A sheet of cardboard was placed under the stimuli to enable the pin to be pushed into the paper. Sheets were positioned in front of the participants' midline. Approximate reaching distance was 450mm.

2.3. Procedure

The order of the bisection experiments in the three modalities and the order of hand use was counterbalanced across 36 participants. All 3 bisection experiments were carried out in the same session. Testing time was approximately 30 minutes in total.

2.3.1. Auditory Line Bisection

Participants sat at a table with the covered speakers in front of them. They placed their head in the chinrest, facing straight ahead. They first listened to two bursts of noise played from each speaker in order from left to right around the arc. They were instructed to focus on the location of the sounds. Participants were then temporarily blindfolded to enable the researcher to calibrate the position of the head with the location of the speakers (requiring a small box to be positioned at the centre of each speaker). These positions were recorded on E-prime software via the infrared sensor on the ceiling. The speakers were concealed and the blindfold removed. The infrared device was secured to the participant's forefinger with the battery pack in the centre of the back of the hand.

For the main task, participants were instructed that they would hear two sounds being played through two different speakers sequentially (the start position, left or right, was counterbalanced). Their task was to estimate the mid-point of those sounds, by moving their finger across the table to the foam, and then using the clicker to indicate when they had the

correct location. They then were told to move their hand back to the start position. They were told to respond as quickly but as accurately as possible. They were given one block of practice, which comprised of 6 trials. 18 trials were completed for each hand.

2.3.2. Visual Line Bisection

Participants were given two sheets of paper for the first hand, and a pen for marking the perceived centre of the line with left and right hand presentations counterbalanced across participants. They were instructed to make a single mark on the line to identify the midpoint. After completion of the task with the first hand the same procedure was carried out with the second hand.

2.3.3. Tactile Line Bisection

Participants were blindfolded. They were trained to run their finger up and down the line four times, with the forefinger. On the fifth scan of the tactile line, they were required to stop their finger at the perceived midpoint, and then, using the other hand, to push a drawing pin into the swell paper sheet at the point they considered to be the midpoint of the line. Participants practiced this with two example lines at the beginning.

The researcher guided the participant's finger to the starting point of the line at the beginning of each trial. Bisections were performed with both hands. Starting hand, second hand and starting position were counterbalanced across participants.

2.4. Data analysis

2.4.1. Visual and Tactile Line Bisection Results

Mean deviation from midpoint for visual and tactile bisections was measured to the nearest 0.5 centimetres. Based on the respective line lengths, deviations were translated into a proportion of the deviation from the midpoints so that -1 represented the left hand end of the interval and + 1 the right. Negative numbers denoted leftward bias and positive numbers

rightward. Individual deviation proportions were averaged across hand used and line lengths and line centre locations.

2.4.2. Auditory Line Bisection Results

Auditory data was recorded and analysed by a bespoke programme, which produced a proportion of the deviation from the midpoint. Negative numbers denoted leftward bias and positive numbers rightward. These were converted from .dat files for use in SPSS. Line bisection deviation data for each hand and line position was averaged for participants before statistical analysis. As with the visual and tactile line bisection data, negative numbers indicate leftward bisection bias and positive numbers rightward bias. The deviations for each hand and line position were combined into mean deviations for each participant position.

3. Results

3.1 Auditory Line Bisection

The mean proportional deviation from the midpoint for the central auditory line locations was -0.051 (SD 0.10). A one-sample *t*-test indicated that this deviation was significantly different to zero ($t = -3.21$, $df = 38$, $p = .003$, $d = 0.51$). This confirmed that there was a leftward bias for auditory line bisection.

3.2. Visual Line Bisection Results

The mean proportional deviation from the midpoint for the visual lines was -0.013 (SD 0.025). A one-sample *t*-test demonstrated that this deviation was significantly different from zero ($t = -3.30$, $df = 38$, $p = .002$, $d = 0.52$), confirming that there was a leftward bisection bias.

3.3. Tactile Line Bisection Results

Tactile lines were bisected on average -0.023 (SD 0.071) away from the centre. A one-sample *t*-test demonstrated that this deviation was significantly different from zero ($t = -2.056$, $df = 38$, $p = .047$, $d = 0.32$), confirming that there was a leftward bisection bias.

3.4. Comparisons across modalities

A one-way ANOVA comparing the deviation from the midpoint across modalities indicated a significant difference in the proportional bisection bias across modalities ($F(2,76) = 3.28$, $p = .043$, $\eta_p^2 = .079$). Once adjusted for multiple comparisons using Bonferroni's method ($\alpha = .05$ hence $\alpha_{adj} = .017$), paired-sample *t*-tests indicated no significant differences between scale of bias between visual and tactile line bisection biases ($t(38) = 0.83$, $p = .411$, $d = 0.19$), between auditory line bisection and visual bisection ($t(38) = 2.29$, $p = .028$, $d = 0.52$) or between tactile and auditory bisection ($t(38) = 1.66$, $p = .104$, $d = 0.32$).

There was a positive relationship between performance on auditory and tactile tasks, such that as leftward deviation decreased in one modality, so it decreased in the other (see Figure 2). However, this relationship was not apparent on scatterplots of the relationship of visual and auditory line bisection (Figure 3), nor for visual and tactile line bisection tasks (Figure 4). The Pearson correlation between auditory and tactile bisection demonstrated a moderate relationship (Pearson's $r = .30$, $n = 39$). Bootstrapping derived 95% confidence intervals (10000 samples) around this coefficient did not include zero (lower = .085, upper = .512): Tactile and visual bisection ($r = -.07$: lower = -.406, upper = .226) and auditory and visual bisection ($r = -.04$, lower = -.324, upper = .233) did not show a substantive correlation. It will be noted that the effect size of the auditory – tactile correlation is outwith the 95% CIs for the other relationships and vice versa.

Figure 2 about here

Figure 3 about here

Figure 4 about here

4. Discussion

This research examined whether or not a leftward line bisection bias, known as pseudoneglect, was present in vision, touch and audition within a group of neurologically typical individuals, using a repeated measures design. This enabled a comparison of performance across modalities. It made use of a new method of adjustment auditory line bisection paradigm, carried out in peripersonal space. The results demonstrate a significant leftward bisection bias in not only vision, but also touch and audition. This evidence supports previous research identifying a leftward bisection bias in vision and touch (e.g. Baek et al, 2002; Brooks et al, 2011; Brooks et al 2016; see Brooks et al 2014 for a review). It is also consistent with claims that the right hemisphere underpins both visuospatial pseudoneglect and representational pseudoneglect due to attentional orienting as a consequence of right hemispheric dominance in spatial processing (Heilman & Van Den Abell, 1979; Reuter-Lorenz, Kinsbourne & Moscovitch, 1990; Brooks et al, 2014). What is particularly novel here is the observation of a pseudoneglect-like lateral bias in detection of tones in peripersonal space. Examination of the relationships between tasks was carried out to assess whether auditory line bisection shared underlying processes with either/or the visual or tactile sensory modalities. Results confirmed a positive correlation between tactile line bisection and auditory line bisection. No noteworthy relationships were found between either vision and audition or vision and touch. These patterns enable us to speculate a little more about the relationship between different domains of pseudoneglect.

The apparent absence of a noteworthy relationship between visual bisection and either tactile or auditory bisection is consistent with the idea that pseudoneglect is not the direct outcome of a single amodal process, but that rather it differs across different stimulus types. However, some amount of caution is necessary in making this conclusion because the 95% confidence intervals around correlations are fairly large in a sample of this size, and bootstrapping methods remain somewhat constrained by the initial sample data: inference to the population level would be strengthened if these relationships prove replicable in future.

These results do not provide convincing support for the claims that auditory spatial attention is dependent on visuospatial processing (e.g. Gori et al., 2014; Gori, Sandini & Burr, 2012). Both the presence of auditory pseudoneglect, and the lack of a close association between auditory pseudoneglect and visual pseudoneglect are in line with the pattern observed in the neglect literature, within which dissociations between neglect syndromes are often observed (e.g. Heilman & Valenstein, 1972; Sinnet et al, 2007). De Renzi et al., (1984) investigated

auditory extinction, often viewed as related to neglect, and also found the phenomenon is often dissociated from visual problems.

A moderate positive correlation between performance on auditory and tactile line bisection tasks was observed. In the auditory line bisection task, participants heard sounds switching between two spatial locations to avoid effects of phasing. Because sounds occurred at one location at one time, a degree of mental representation was required. If it is accepted that sequential discovery means that tactile line bisection also requires the building up of a representation is an example of representational pseudoneglect (Brooks et al, 2011; 2014; 2016), then it is apparent that both our auditory and tactile tasks rely on representational processes. The moderate correlation between these two tasks, may well reflect shared mechanisms of spatial representation in the auditory and tactile bisection tasks. We note, though, that the moderate size of this correlation clearly allows for other, possibly modality specific, processes to be at work.

The three pseudoneglect tasks in this study were designed to be as comparable as possible, but of necessity, there were differences in the dimensions of the stimuli in the auditory versus the tactile and linear conditions. These were an inevitable consequence of the physical apparatus necessary to present acoustically unbiased stimuli but it is possible that differences *between* conditions may have arisen from the use of an arc array of speakers in the auditory condition compared to the straight arrays in the other conditions, and from differences in the physical size of the intervals in the acoustic versus the other conditions. Nonetheless, the proportional measurements used *are* directly comparable across conditions, and the main conclusions of lateral bias rest on one-sample tests and do not rely on between-condition comparisons.

There is a good deal of heterogeneity within the now extensive literature on pseudoneglect in the visual domain, with various different tasks such as the Landmark task, the Greyscales task and traditional method of adjustment line bisection tasks behaving in somewhat different ways when challenged by different task conditions and or samples (for reviews see Brooks et al, 2014 and Jewell & McCourt, 2000). A specific example is discussed by Brooks et al (2015: in press) who review past literature which suggests a rightward drift across adult ageing in some lateral bias tasks (Landmark tasks) whilst evidence for such a drift is more equivocal in more traditional line bisection tasks. It is possible that a traditional line bisection

task invokes a greater degree of mental representation than does the landmark task, a task which appears almost entirely perceptual in nature.

This argument is consistent with the suggestion that a qualitative distinction can be drawn between perceptual and representational pseudoneglect – a suggestion that has received a good deal of corroborative support from various different studies (McGeorge et al, 2007; Darling et al, 2012) and which would reflect the evident dissociation between perceptual and representational neglect (Beschin et al, 2002; 2005; Della Sala et al, 2004). The present data are consistent with this suggestion – with visual line bisection being located further towards the perceptual pole of this dichotomy and auditory and tactile tasks being located further towards the representational pole. It would therefore be informative in future to investigate relationships between auditory and tactile bisection tasks and visual tasks that are closely matched on representational demands. A simple way to do this would be to use a sequentially-presented visual bisection task. It also bears consideration that investigations of visual-spatial working memory have suggested that spatial processes may be more activated when items are presented sequentially rather than when they are presented simultaneously (Darling, Della Sala & Logie, 2009). This, in turn, is suggestive of separate mechanisms of simultaneous visual-perceptual processing and sequential-representational processing both of which might be independently susceptible to different pseudoneglect lateral biases, and hence, presumably, localisable to subtly different parts of the right hemisphere. Such issues should be addressed in future research. Similarly, future research should focus on the relationship between attention and perceptual components in representational and perceptual pseudoneglect: presumably attentional biases could apply to representations whilst purely perceptual biases would not, and so cross-modal pseudoneglect effects may be a consequence of a general attentional bias, whilst perceptual biases may be more direct reflections of asymmetries of basic visual processing.

4.1 Conclusions

The results of this research lead to three important-principal conclusions. Firstly, there was strong evidence for pseudoneglect in visual, tactile and auditory tasks presented in near space – the latter observation being entirely novel. Secondly, auditory and tactile line bisection task biases shared some underlying variance, which was not shared with visual line bisection. Thirdly (and following on from the first two conclusions), whilst it remains likely that there are some distinct sensory-specific mechanisms in spatial processing, some

mechanisms that underlie mental *representations* of space may be shared between modalities.

~~Both modality specific and amodal mechanisms can be subject to independent lateral biases.~~

One might argue that this is in line with observations from visually impaired individuals, who show pseudoneglect in tactile and mental number line bisection (Cattaneo et al. 2010; Cattaneo, et al., 2011), and who also demonstrate spatial mental representational skills that are as strong or stronger than sighted people (e.g. Eardley et al., 2015).

Overall, this study clearly demonstrates a leftward bisection bias in an auditory line bisection task. We found no evidence that this bias was mediated by visual perceptual processing, even though the common leftward bisection bias indicates that both tasks are likely to be influenced by processing in the right hemisphere. Furthermore, auditory pseudoneglect seems to share processes with tactile pseudoneglect, which suggest a shared role of mental representation in both tasks.

References

Baek, M. J., Lee, B. H., Kwon, J. C., Park, J. M., Kang, S. J., Chin, J., Heilman, K. M., & Na, D. L. (2002). Influence of final search direction on tactile line bisection in normal subjects. *Neurology*, *58*(12), 1833-1838.

Banerjee, S., Snyder, A. C., Molholm, S., & Foxe, J. J. (2011). Oscillatory alpha-band mechanisms and the deployment of spatial attention to anticipated auditory and visual target locations: supramodal or sensory-specific control mechanisms? *The Journal of Neuroscience*, *31*(27), 9923-9932.

Bartolomeo, P., D' Erme, P., & Gainotti, G. (1994). The relationship between visuospatial and representational neglect. *Neurology*, *44*(9), 1710–1714

Barbieri, C., & De Renzi, E. (1989). Patterns of neglect dissociation. *Behavioural Neurology*, *2*(1), 13-24.

Benwell, C. S., Harvey, M., & Thut, G. (2014). On the neural origin of pseudoneglect: EEG-correlates of shifts in line bisection performance with manipulation of line length. *Neuroimage*, *86*, 370-380.

Beschin, N., Basso, A., & Della Sala, S. (2000). Perceiving left and imagining right: Dissociation in neglect. *Cortex*, *36*(3), 401-414.

Beschin, N., Cocchini, G., Della Sala, S., & Logie, R. H. (1997). What the eyes perceive, the brain ignores: a case of pure unilateral representational neglect. *Cortex*, *33*(1), 3–26.

Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: effects of hemispace on a tactile line bisection task. *Neuropsychologia*, *18*(4), 491-498.

Brodie, E. E., & Dunn, E. M. (2005). Visual line bisection in sinistrals and dextrals as a function of hemispace, hand, and scan direction. *Brain and cognition*, *58*(2), 149-156.

Brodie, E. E., & Pettigrew, L. E. L. (1996). Is left always right? Directional deviations in visual line bisection as a function of hand and initial scanning direction. *Neuropsychologia*, *34*(5), 467–470

Brooks, J. L., Della Sala, S., & Darling, S. (2014). Representational Pseudoneglect: A Review. *NeuroPsychol Rev.* *24*, 148-165

Brooks, J. L., Della Sala, S., & Logie, R. H. (2011). Tactile rod bisection in the absence of visuo-spatial processing in children, mid-age and older adults. *Neuropsychologia*, *49* (12), 3392-3398.

Bjoertomt, O., Cowey, A., & Walsh, V. (2002). Spatial neglect in near and far space investigated by repetitive transcranial magnetic stimulation. *Brain*, *125* (9), 2012-2022.

Bowers, D. & Heilman, K. M. (1980). Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia*, *18*, 491 - 498.

Brodie, E. E., & Pettigrew, L. E. (1995). Spatial field advantages for tactile line bisection as a function of hemispheric specialisation inferred from dichotic listening. *Neuropsychologia*, *33*(1), 53-61.

Brooks, J. L., Darling, S., Malvaso, C., & Della Sala, S. (2016). Adult developmental trajectories of pseudoneglect in the tactile, visual and auditory modalities and the influence of starting position and stimulus length. *Brain and cognition*, *103*, 12-22.

Brooks, J. L., Della Sala, S., & Logie, R. (2011). Tactile rod bisection in the absence of visuospatial processing in children, mid-age and older adults. *Neuropsychologia*, *49*(12), 3392–3398

Brooks, J. L., Della Sala, S., & Darling, S. (2014). Representational pseudoneglect: a review. *Neuropsychology review*, *24*(2), 148-165.

Bushara, K. O., Weeks, R. A., Ishii, K., Catalan, M. J., Tian, B., Rauschecker, J. P., & Hallett, M. (1999). Modality-specific frontal and parietal areas for auditory and visual spatial localization in humans. *Nature neuroscience*, 2(8), 759-766.

Cantagallo, A., & Della Sala, S. (1998). Preserved insight in an artist with extrapersonal spatial neglect. *Cortex*, 34(2), 163-189.

Cardinali, L., Brozzoli, C. & Farnè, A. (2009). Peripersonal Space and Body Schema: Two Labels for the Same Concept? *Brain Topography*, 21(3), 252-260.

Cattaneo, Z., Cecchetto, C., & Papagno, C. (2015). Deaf Individuals Show a Leftward Bias in Numerical Bisection. *Perception*, 0, 1-9

Cattaneo, Z., Fantino, M., Tinti, C., Pascual-Leone, A., Silvanto, J., & Vecchi, T. (2011). Spatial biases in peripersonal space in sighted and blind individuals revealed by a haptic line bisection paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, 37(4), 1110.

Cattaneo, Z., Fantino, M., Tinti, C., Silvanto, J., & Vecchi, T. (2010). Crossmodal interaction between the mental number line and peripersonal haptic space representation in sighted and blind individuals. *Attention, Perception, & Psychophysics*, 72(4), 885–890.

Cattaneo, Z., Silvanto, J., Pascual-Leone, A., & Battelli, L. (2009). The role of the angular gyrus in the modulation of visuospatial attention by the mental number line. *NeuroImage*, 44(2), 563–568

Clarke, S., & Thiran, A. B. (2004). Auditory neglect: what and where in auditory space. *Cortex*, 40(2), 291-300.

Corral, M. J., & Escera, C. (2008). Effects of sound location on visual task performance and electrophysiological measures of distraction. *NeuroReport*, 19(15), 1535-1539.

Corsi, P. M. (1972). Human memory and the medial temporal lobe region of the brain [PhD thesis]. *McGill University, Montreal*.

- Coslett, H. B. (1997). Neglect in vision and visual imagery: a double dissociation. *Brain*, *120*(7), 1163-1171.
- Darling, S., Logie, R. H. & Della Sala, S. (2012). Representational pseudoneglect in line bisection. *Psychonomic Bulletin and Review*, *19*, 879-883
- De Renzi, E., Gentilini, M., & Pattacini, F. (1984). Auditory extinction following hemisphere damage. *Neuropsychologia*, *22*(6), 733-744.
- De Schotten, M. T., Dell'Acqua, F., Forkel, S. J., Simmons, A., Vergani, F., Murphy, D. G., & Catani, M. (2011). A lateralized brain network for visuospatial attention. *Nature neuroscience*, *14*(10), 1245-1246.
- Della Sala, S., Logie, R. H., Beschin, N., & Denis, M. (2004). Preserved visuo-spatial transformations in representational neglect. *Neuropsychologia*, *42*(10), 1358-1364.
- Denis, M., Beschin, N., Logie, R.H. & Della Sala, S. (2002). Visual Perception and Verbal Descriptions as Sources for Generating Mental Representations: Evidence from Representational Neglect. *Cognitive Neuropsychology*, *19* (2), 97-112.
- Deouell, L. Y., Bentin, S., & Soroker, N. (2000). Electrophysiological evidence for an early (pre-attentive) information processing deficit in patients with right hemisphere damage and unilateral neglect. *Brain*, *123*(2), 353-365.
- Deouell, L. Y., Hämäläinen, H., & Bentin, S. (2000). Unilateral neglect after right-hemisphere damage: contributions from event-related potentials. *Audiology and Neurotology*, *5*(3-4), 225-234.
- Dufour, A., Touzalin, P., & Candas, V. (2007). Rightward shift of the auditory subjective straight ahead in right- and left-handed subjects. *Neuropsychologia*, *45*(2), 447-453.
- Driver, J., & Spence, C. (1998). Attention and the crossmodal construction of space. *Trends in cognitive sciences*, *2*(7), 254-262.

Eardley, A. F., Edwards, G., Malouin, F., & Kennedy, J. M. (2016). Allocentric Spatial Performance Higher in Early-Blind and Sighted Adults Than in Retinopathy-of-Prematurity Adults. *Perception*, *45*(3), 281-299.

Eimer, M., Velzen, J. V., & Driver, J. (2002). Cross-modal interactions between audition, touch, and vision in endogenous spatial attention: ERP evidence on preparatory states and sensory modulations. *Cognitive Neuroscience, Journal of*, *14*(2), 254-271.

Farah, M. J., Wong, A. B., Monheit, M. A., & Morrow, L. A. (1989). Parietal lobe mechanisms of spatial attention: modality-specific or supramodal?. *Neuropsychologia*, *27*(4), 461-470.

Fink, G. R., Marshall, J. C., Shah, N. J., Weiss, P. H., Halligan, P. W., Grosse-Ruyken, M., K. Ziemons, K., Zilles, K. & Freund, H. J. (2000). Line bisection judgments implicate right parietal cortex and cerebellum as assessed by fMRI. *Neurology*, *54*(6), 1324-1331.

Gainotti, G. (2010). The role of automatic orienting of attention towards ipsilesional stimuli in non-visual (tactile and auditory) neglect: a critical review. *Cortex*, *46*(2), 150-160.

Gamberini, L., Seraglia, B., & Priftis, K. (2008). Processing of peripersonal and extrapersonal space using tools: Evidence from visual line bisection in real and virtual environments. *Neuropsychologia*, *46*(5), 1298-1304.

Gentaz, E., Baud-Bovy, G., & Luyat, M. (2008). The haptic perception of spatial orientations. *Experimental brain research*, *187*(3), 331-348.

Gobel, S. M., Calabria, M., Farne, A., & Rossetti, Y. (2006). Parietal rTMS distorts the mental number line: simulating 'spatial' neglect in healthy subjects. *Neuropsychologia*, *44*(6), 860-868

Gori, M., Sandini, G., & Burr, D. (2012). Development of visuo-auditory integration in space and time. *Frontiers in Integrative Neuroscience*, *6*, 77, 1-8.

Gori, M., Sandini, G., Martinoli, C. & Burr, D. C. (2014). Impairment of auditory spatial localization in congenitally blind human subjects. *Brain*, *137*, 288-293

Guariglia, C., Padovani, A., Pantano, P., & Pizzamiglio, L. (1993). Unilateral neglect restricted to visual-imagery. *Nature*, *364*(6434), 235–237

Hach, S., & Schütz-Bosbach, S. (2012). Touching base: The effect of participant and stimulus modulation factors on a haptic line bisection task. *Laterality: Asymmetries of Body, Brain and Cognition*, *17*(2), 180-201.

Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: evidence from visual neglect. *Trends in cognitive sciences*, *7*(3), 125-133.

Hausmann, M., Ergun, G., Yazgan, Y., & Güntürkün, O. (2002). Sex differences in line bisection as a function of hand. *Neuropsychologia*, *40*(3), 235-240.

Heilman, K. M., & Valenstein, E. (1972). Frontal lobe neglect in man. *Neurology*, *22*(6), 660-660.

Heilman, K. M., & Van Den Abell, T. (1979). Right hemispheric dominance for mediating cerebral activation. *Neuropsychologia*, *17*(3–4), 315–321

Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: a review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia*, *38*(1), 93-110.

Kinsbourne, M. (1970). A model for the mechanism of unilateral neglect of space. *Transactions of the American Neurological Association*, *95*: 143-46

Knudsen, E. I. (2011). Control from below: the role of a midbrain network in spatial attention. *European Journal of Neuroscience*, *33*(11), 1961-1972.

Lessard, N., Pare, M., Lepore, F., & Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature*, *395*(6699), 278-280.

- Logie, R. H., Della Sala, S., Beschin, N., & Denis, M., (2005). Dissociating mental transformations and visuo-spatial storage in working memory: Evidence from representational neglect. *Memory*, *13*(3-4), 430-434.
- Longo, M. R., & Lourenco, S. F. (2006). On the nature of near space: effects of tool use and the transition to far space. *Neuropsychologia*, *44*(6), 977–981
- Longo, M. R., & Lourenco, S. F. (2007). Spatial attention and the mental number line: Evidence for characteristic biases and compression. *Neuropsychologia*, *45*(7), 1400-1407.
- Longo, M. R., & Lourenco, S. F. (2010). Bisecting the mental number line in near and far space. *Brain and Cognition*, *72*(3), 362–367
- Lourenco, S. F., & Longo, M. R. (2009). Multiple spatial representations of number: evidence for co-existing compressive and linear scales. *Experimental Brain Research*, *193*(1), 151–156
- McCourt, M. E., & Garlinghouse, M. (2000). Asymmetries of visuospatial attention are modulated by viewing distance and visual field elevation: pseudoneglect in peripersonal and extrapersonal space. *Cortex*, *36*(5), 715–731
- McGeorge, P., Beschin, N., Colnaghi, A., Rusconi, M.L. & Della Sala, S. (2007). A lateralized bias in mental imagery: Evidence for representational pseudoneglect. *Neuroscience Letters*, *421*, 259 - 263.
- Mattingley, J. B., Berberovic, N., Corben, L., Slavin, M. J., Nicholls, M. E., & Bradshaw, J. L. (2004). The greyscales task: a perceptual measure of attentional bias following unilateral hemispheric damage. *Neuropsychologia*, *42* (3), 387-394.
- Mesulam, M. M. (1999). Spatial attention and neglect: parietal, frontal and cingulate contributions to the mental representation and attentional targeting of salient extrapersonal events. *Phil. Trans. R. Soc. London B*, *354*, 1325-1346

Milner, A. D., Harvey, M., Roberts, R. C., & Forster, S. V. (1993). Line bisection errors in visual neglect: Misguided action or size distortion?. *Neuropsychologia*, *31*(1), 39-49.

Nicholls, M., & Loftus, A.M. (2007). Pseudoneglect and neglect for mental alphabet lines. *Brain Research*, *1152*, 130-138.

Nicholls, M. E. R. & McIlroy, A. M. (2010). Spatial Cues Affect Mental Number Line Bisections. *Experimental Research*, *57*. 315-319

Ocklenburg, S., Hirnstein, M., Hausmann, M., & Lewald, J. (2010). Auditory space perception in left-and right-handers. *Brain and cognition*, *72*(2), 210-217.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Oliveri, M., Rausei, V., Koch, G., Torriero, S., Turriziani, P., & Caltigrono, C. (2004). Overestimation of numerical distances in the left side of space. *Neurology*, *63*(11), 2139–2141

Ortigue, S., Viaud-Delmon, I., Annoni, J. M., Landis, T., Michel, C., Blanke, O., Vuilleumier, P., & Mayer, E. (2001). Pure representational neglect after right thalamic lesion. *Annals of neurology*, *50*(3), 401-404.

Ortigue, S., Viaud-Delmon, I., Michel, C. M., Blanke, O., Annoni, J. M., Pegna, A. Mayer, E., Spinelli, L., & Landis, T. (2003). Pure imagery hemi-neglect of far space. *Neurology*, *60*(12), 2000-2002.

Parton, A., Malhotra, P., & Husain, M. (2004). Hemispatial neglect. *Journal of Neurology, Neurosurgery & Psychiatry*, *75*(1), 13-21.

Patston, L. L., Corballis, M. C., Hogg, S. L., & Tippett, L. J. (2006). The Neglect of Musicians Line Bisection Reveals an Opposite Bias. *Psychological Science*, *17*(12), 1029-1031.

- Piccardi, L., Bianchini, F., Zompanti, L., & Guariglia, C. (2008). Pure representational neglect and navigational deficits in a case with preserved visuo-spatial working memory. *Neurocase*, *14*(4), 329-342.
- Reuter-Lorenz, P. A., Kinsbourne, M., & Moscovitch, M. (1990). Hemispheric control of spatial attention. *Brain and cognition*, *12*(2), 240-266.
- Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, F., Hillyard, S. A., & Neville, H. J. (1999). Improved auditory spatial tuning in blind humans. *Nature*, *400*(6740), 162-166.
- Rueckert, L., Deravanesian, A., Baboorian, D., Lacalamita, A., & Reppinger, M. (2002). Pseudoneglect and the cross-over effect. *Neuropsychologia*, *40*(2), 162-173.
- Sinnett, S., Juncadella, M., Rafal, R., Azanón, E., & Soto-Faraco, S. (2007). A dissociation between visual and auditory hemi-inattention: Evidence from temporal order judgements. *Neuropsychologia*, *45*(3), 552-560.
- Soroker, N., Calamaro, N., & Myslobodsky, M. (1995). "McGurk illusion" to bilateral administration of sensory stimuli in patients with hemispatial neglect. *Neuropsychologia*, *33*(4), 461-470.
- Sosa, Y., Teder-Sälejärvi, W. A., & McCourt, M. E. (2010). Biases of spatial attention in vision and audition. *Brain and cognition*, *73*(3), 229-235.
- Spence, C., & Driver, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(4), 1005.
- Spence, C., & Driver, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception & psychophysics*, *59*(1), 1-22.
- Van Kerkhoff, L., & Lebel, L. (2006). Linking knowledge and action for sustainable development. *Annu. Rev. Environ. Resour.*, *31*, 445-477.

Varnava, A., Dervinis, M., & Chambers, C. D. (2013). The predictive nature of pseudoneglect for visual neglect: evidence from parietal theta burst stimulation. *PloS one*, 8(6), e65851.

Varnava, A., McCarthy, M., & Beaumont, J. G. (2002). Line bisection in normal adults: direction of attentional bias for near and far space. *Neuropsychologia*, 40(8), 1372–1378

Wallace, M. T., & Stein, B. E. (2001). Sensory and multisensory responses in the newborn monkey superior colliculus. *The Journal of Neuroscience*, 21(22), 8886-8894.

Wu, C. T., Weissman, D. H., Roberts, K. C. & Woldorff, M. G. (2007). The neural circuitry underlying the executive control of auditory spatial attention. *Brain Research*. 1134, 187–198.

Zimmer, U., Lewald, J., Erb, M., & Karnath, H. O. (2006). Processing of auditory spatial cues in human cortex: an fMRI study. *Neuropsychologia*, 44(3), 454-461.

Zimmer, U., & Macaluso, E. (2005). High binaural coherence determines successful sound localization and increased activity in posterior auditory areas. *Neuron*, 47(6), 893-905.

List of Figures:

Figure 1: Position of the speakers underneath the black, acoustically transparent cloth. The speakers were positioned on top of a 1-inch high foam base. The midpoint was 57cm from the base of the chin rest. All speakers were approximately 70cm from the crown of the head. The visual and tactile sheets were positioned on the table in front of the participant, on top of the acoustically transparent cloth.

Figure 2: Relationship between Tactile line bisection and auditory line bisection

Figure 3: Relationship between auditory line bisection and visual line bisection

Figure 4: Relationship between visual line bisection and tactile line bisection