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International Journal of Psychophysiology 50 (2003) 165–180

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

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Multisensory temporal order judgments: the role of hemispheric redundancy

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Received 20 November 2002; accepted 17 January 2003

Abstract

Participants made unspeeded 'Which modality came first?' temporal order judgments (TOJs) in response to pairs of auditory and visual stimuli presented at varying stimulus onset asynchronies (SOAs), using the method of constant stimuli. The presentation of auditory and visual stimuli from different spatial positions facilitated performance (i.e. just noticeable differences were lowered) only when the stimuli were presented across the body midline (Experiment 4), but not when both stimuli were either placed on the body midline (Experiments 1–3), or else within the same hemifield (Experiment 5). These results demonstrate that hemispheric redundancy may account for the facilitatory effects reported in previous multisensory TOJs research when stimuli were presented from different spatial locations. Our results also show that the accuracy with which people can make multisensory TOJs is unaffected by the predictability of target stimulus locations, suggesting little role for spatial attention in this aspect of multisensory temporal perception.

Keywords: Multisensory perception; Temporal order judgments

1. Introduction

In a typical temporal order judgment (TOJ) experiment, participants are presented with pairs of target stimuli at various stimulus onset asynchronies (SOAs) and asked to judge which stimulus appeared first. In multisensory TOJ experiments, the two stimuli are presented from different sensory modalities, and participants are normally required to judge which modality was presented first. Previous to our recent work (Spence et al., 2003, 2001; Zampini et al., in press), all previous multisensory TOJ studies to our knowledge presented stimulation to different sensory modalities from different spatial locations: auditory stimuli over headphones, visual stimuli from a light source in front of the participant, and tactile stimuli delivered to the participant's hand placed by their side (e.g. Bald et al., 1942;

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doi:10.1016/S0167-8760(03)00132-6

Dinnerstein and Zlotogura, 1968; Hamlin, 1895; Jaskowski et al., 1990; Rutschmann and Link, 1964; Smith, 1933; Teatini et al., 1976; Whipple et al., 1899; though note the solitary exception of a rarely cited study reported by Gengel and Hirsh, 1970).

The fact that the pairs of target stimuli used in previous multisensory TOJ studies were presented from different spatial locations raises two potentially important problems regarding the interpretation of the results from those studies. Firstly, participants may have based their multisensory TOJ responses on which *location* was stimulated first, rather than on the basis of which *sensory modality* they perceived first—effectively turning a '*modality*' TOJ into a '*spatial*' TOJ. Alternatively, participants may have used the presence of any redundant spatial cues (about which location came first) to augment or enhance, the veridicality of their responses about which modality came first. Any such strategy would presumably have resulted in an apparent overestimation of the precision of multisensory TOJ performance in previous research.

Several recent studies from this laboratory have supported this prediction, demonstrating that the precision with which people make multisensory TOJs is higher when the target stimuli are presented from different positions, rather than from the same position (Spence et al., 2001, 2003; Zampini et al., in press). For example, Spence et al. (2001) demonstrated that the just noticeable difference (JND; i.e. the smallest temporal interval between two stimuli needed for participants to be able to judge which stimulus comes first on 75% of trials) was 37 ms for pairs of visual and tactile stimuli presented from *different* spatial positions (one positioned 25 cm or 27° of visual angle, to either side of central fixation), as compared to 68 ms when the two stimuli were presented from the *same* position on either the left or right of fixation (see also Spence et al., 2003, Experiment 1). A similar significant spatial modulation of the JND for audiovisual TOJs was also reported by Spence et al. (2003, Experiment 2; mean JNDs of 42 ms vs. 53 ms, respectively) and Zampini et al. (in press, Experiment 1; mean JNDs of 22 ms vs. 32 ms, respectively).[1] The goal of the present research was to explore further the relation between spatial separation and temporal precision in audiovisual TOJs; in particular, to assess the role of hemispheric redundancy and spatial expectancy in modulating these effects.

In the first experiment, we investigated whether the same spatial redundancy effect on audiovisual TOJs could be demonstrated using a paradigm more closely modelled on the seminal studies of Hirsh and Sherrick (1961) and others (e.g. Dinnerstein and Zlotogura, 1968; Jaskowski et al., 1990; Rutschmann and Link, 1964). The visual stimuli in Experiment 1 were always presented from an LED placed directly in front of the participant, while the auditory stimuli could either be presented over headphones (Different Position condition; just as in Hirsh and Sherrick, 1961, and the majority of previous research) or from an external loudspeaker cone situated directly behind the target LED (Same Position condition). We predicted that if the spatial confound is as important as our recent multisensory TOJ research suggests then the JNDs reported in Experiment 1 should be greater in the Same Position (i.e. external loudspeaker) condition than in the Different Position (i.e. headphone) condition. Any such finding would support the claim of a potential spatial redundancy confound in previously published multisensory TOJ studies.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Thirteen participants (mean age of 25 years) were recruited to take part in this experiment, which took approximately 30 min to complete. Visual acuity was normal or corrected-to-normal,

[1] This surprising result runs counter to the findings from many previous intramodal studies of perception and attention that have shown better perceptual processing for combinations of stimuli presented from the same rather than from different locations/objects (e.g. Duncan, 1984; Egly et al., 1995; O'Craven et al., 1999). See Spence et al. (2003) for an in-depth discussion of the variety of possible causes underlying such a pattern of results.

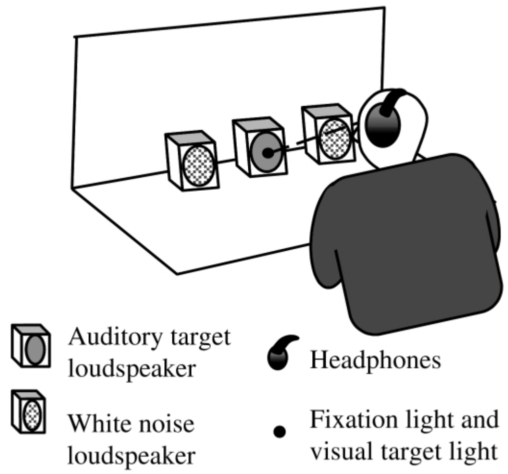

Fig. 1. Schematic view of the participant and the experimental setup used in Experiments 1 and 2. The dotted line shows the direction of fixation.

and all participants reported normal hearing. All participants were naïve as to the purpose of the study, and all gave their informed consent prior to their taking part in the experiment. All of the experiments reported here were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.1.2. Apparatus and materials

The experiment was conducted in a completely dark sound-attenuated room. A red light-emitting diode (LED; luminance of 64.3 cd/m^2) was placed on the table 62 cm in front of the participant, serving as a central fixation point. Eye position was monitored by the experimenter using a CCTV camera (Panasonic BP310/B) situated directly behind, and slightly above, the target fixation light. Participants were seated at a table facing straight-ahead, with their head resting on a chin rest. The auditory stimuli were either presented from a loudspeaker cone (VE100AO) situated directly behind the fixation light, or from a pair of headphones (Philips SBC HL135) that participants wore in the different position blocks (see Fig. 1). The auditory stimuli consisted of the presentation of a 9 ms white noise burst at an intensity of 82 dB (A; equated for the two means of presentation) as measured from the participants' ear position. The visual stimuli consisted of the onset of the fixation LED for 9 ms. The stimuli were presented for such a short duration to ensure that at even the shortest SOA, the two stimuli would not overlap, thus avoiding any multisensory integration effects due to simultaneous presentation of stimuli. The use of a short duration also enabled us to compare our results directly to other studies using the same design (e.g. see Experiment 4). No specific attempt was made to try and match the intensities of the clearly suprathreshold auditory and visual stimuli (cf. Spence et al., 2001). White noise was presented continuously at 75 dB (A) throughout each experimental block from two loudspeaker cones, one situated 30 cm to either side of central fixation to mask any noise made by the participants.

Participants normally kept their thumbs on two separate keys placed vertically one above the other on a hand-held response pad. They were instructed to depress the upper key on trials where the auditory stimulus appeared to have been presented first, and to depress the lower key whenever the visual stimulus appeared to have been presented first. The identity of the response made by the participant was indicated by the illumination of one of the two yellow LEDs placed directly above and below the fixation light for 600 ms immediately after a response had been detected. The illumination of the upper light with an 'S' printed on it indicated a 'sound-first' response, and the illumination of the lower light with an 'L' printed on it indicated a 'light-first' response. The feedback lights gave no indication as to whether the participant's response was correct or not, but simply indicated to the participant, which response they had made and so helped to prevent any erroneous responding on the part of our participants. Presentation of the stimuli and monitoring of the participants' responses was controlled by an IBM 486 compatible microcomputer using a program written in Turbo Pascal 7.0. Timing was controlled by a custom timing routine that interfaced to the LEDs, the loudspeaker cone, the headphones and the response keys.

2.1.3. Design

There were two within-participants factors: Relative Stimulus Position (Same vs. Different) and

SOA (−200 ms, −90 ms, −55 ms, −30 ms, −20 ms, +20 ms, +30 ms, +55 ms, +90 ms and +200 ms; negative SOAs indicate that the auditory stimulus was presented first, whereas positive values indicate that the visual stimulus was presented first). The Same and Different Position conditions were presented in separate blocks of experimental trials in Experiment 1. These blocks were alternated with the order of presentation counterbalanced across participants. The 10 possible SOAs were presented twice within each of the two blocks of 20 practice trials, and four times within each of the eight subsequent blocks of 40 experimental trials.

2.1.4. Procedure

The participants were instructed to maintain their fixation on the central LED throughout each block of trials. The first stimulus was presented after a delay of 750 ms following the presentation of any visual feedback and the second stimulus after a further interval (determined by the SOA specified for that particular condition). The participants were informed about where the stimuli would appear from (either from the headphones or from the external loudspeaker) at the beginning of each experimental block. The task was unspeeded, and participants were informed that they should respond only when confident of their response. If participants responded prior to the onset of the first stimulus, or else failed to make a response before the trial was terminated (3500 ms after the onset of the first stimulus), error feedback was presented. This error feedback consisted of the flickering of the fixation light for 1000 ms. Such anticipations or non-responses occurred on less than 1% of trials overall, and were not analysed. Otherwise, the participant's response was indicated by the illumination of one of the central feedback lights for 500 ms after their response was detected.

2.2. Results

The proportion of 'light first' responses was converted to its equivalent Z-score assuming a cumulative normal distribution (cf. Finney, 1964). The intermediate eight SOAs were used to calculate a best-fitting straight line for each participant

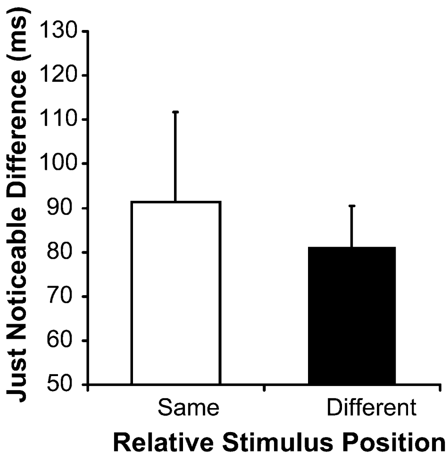

Fig. 2. Just noticeable differences (JNDs) for the two audiovisual stimulus pairs in Experiment 1. The errors bars represent the within-observer S.E. of the mean. The results show that when audiovisual stimulus pairs were presented on the body midline and from a fixed position for each block of trials, performance was not facilitated by the presence of redundant spatial cues.

for each condition. The ±200 ms points were excluded from this computation because most participants performed nearly perfectly at this interval, and so no additional variance was accounted for by these points (cf. Spence et al., 2001).[2] The slopes and intercepts from these best-fitting lines were used to calculate two standard measures of perceptual performance: the JND (JND = 0.675/slope) and the point of subjective simultaneity (PSS), which represents the average interval by which one stimulus has to lead the other in order for the two to be judged as occurring at the same time (i.e. for participants to make the sound first and light first response with equal probability). These two performance measures were calculated separately for each condition for every participant, and are shown in Fig. 2 and Table 1. The JND and PSS data were submitted to paired samples *t*-

[2] In fact, the inclusion of the ±200 ms points would actually have resulted in an artifactual reduction in slope. Nevertheless, inclusion of these large SOAs values (200 ms) is still important from a methodological point of view, as it gives participants the sense that they can perform the TOJ task, and so helps to maintain their levels of motivation during the experiment itself.

Table 1
Summary statistics from the five multisensory temporal order judgment (TOJ) experiments reported in this study

Experiment	Relative stimulus position	JND (1)		PSS (2)	
		M	S.E.M.	*M*	S.E.M.
1	Same	91.4	20.3	30.0	15.3
	Different	81.2	9.3	27.6	9.2
2	Same	95.9	30.9	12.9	14.4
	Different	69.3	15.4	−1.5	21.0
3	Same	88.1	11.8	5.7	6.3
	Different	91.6	21.2	24.4	11.6
4	Same	73.1	10.2	33.1	18.4
	Different	58.2	7.7	46.6	13.7
5	Same	67.5	9.7	21.9	7.8
	Different	84.9	20.9	42.2	9.1

(1) Just noticeable differences (JNDs) were calculated for each participant by averaging the stimulus onset asynchrony (SOA) at which the best fitted line crossed the 0.75 point from the SOA at which the same line crossed the 0.25 point. Values are in milliseconds.

(2) +ve Point of subjective simultaneity (PSS) values indicate that the visual stimulus was presented first, whereas −ve values indicate that the auditory stimulus was presented first. These values were determined by averaging the PSS from the best-fitted line for each individual participant. Values are in milliseconds.

tests comparing the Same and Different Position conditions. Two participants were removed from the analysis because their estimated PSS values were greater than 200 ms, which was beyond the SOA range tested (see Spence et al., 2001, for similar criteria for exclusion). Neither the analysis of the JND data [$t(10)=0.54$, $P=0.60$, n.s.], nor the analysis of the PSS data [$t(10)=0.23$, $P=0.82$, n.s.], revealed any significant difference in performance between the Same and Different Position conditions. The *t*-tests revealed that the PSS values observed were significantly different from 0 ms in the Different Position condition [$t(10)=2.98$, $P<0.05$], and were marginally significant in the Same Position condition [$t(10)=1.95$, $P=0.08$].

2.3. Discussion

The analysis of the data from Experiment 1 did not reveal a significant difference in the precision of multisensory TOJs between the Same and Different Position conditions. This result is somewhat surprising given that previous research from this laboratory has repeatedly shown better performance (i.e. lower JNDs) when pairs of auditory and visual stimuli are presented from different sides rather than from the same spatial location (Spence et al., 2003; Zampini et al., in press).

One possible explanation for the null effect of Relative Stimulus Position reported in Experiment 1 relates to the fact that the auditory and visual stimuli were presented from fixed positions in each block of trials. While this design feature matches many of the older published multisensory TOJ studies on which Experiment 1 was based (e.g. Hirsh and Sherrick, 1961), it represents a change from our previous multisensory TOJ studies (e.g. Spence et al., 2001, 2003; Zampini et al., in press), in which the position of visual and auditory stimuli was always *unpredictable* on every trial. While the former condition would allow participants to focus their spatial attention for each modality on a particular spatial location (i.e. directing their auditory attention to the location of the headphones while directing their visual attention to the location of the LED in front of them), the latter condition requires attention to be divided between both possible stimulus locations in both modalities throughout each block of trials (e.g. see Spence and Driver, 1996).

Several previous studies have shown more pronounced spatial attention effects under conditions where target location is made unpredictable (cf. Posner, 1978; Posner et al., 1980; Spence and Driver, 1996). Therefore, we thought it possible that the requirement to divide spatial attention between two different (and widely-separated) spatial locations in our previous research may have resulted in a spatial modulation of TOJ performance that was absent when the same fixed positions were repeatedly stimulated for each modality throughout each block of trials in the present Experiment 1 (and by implication in the majority of previous multisensory TOJ studies). Moreover, previous research has demonstrated that the predictability of the stimulus position will produce a benefit only when it is cued on a *trial-by-trial basis* but not when it is *blocked* through a block of trials (Posner et al., 1980).[3] In the next experiment, we attempted to assess this spatial predictability account of the null effect of Relative Stimulus Position reported in Experiment 1 by randomising the two possible configurations of stimulus presentation (hence making the design more similar to that used in our previous work; e.g. Spence et al., 2003; Zampini et al., in press). Comparison of the results of Experiments 1 and 2 would also allow us to assess the effects of spatial uncertainty (i.e. spatial attention) on the accuracy with which people can make multisensory TOJs.

3. Experiment 2

3.1. Methods

3.1.1. Participants

Eleven participants (mean age of 26 years) were recruited to take part in this experiment, which took approximately 30 min to complete. All participants were naïve as to the purpose of the study, and none had taken part in the previous experiment.

3.1.2. Apparatus, materials, design and procedure

These were the same as in Experiment 1 with the sole exception that the spatial location from which the auditory stimulus was presented on each trial was now made entirely unpredictable. That is, the 20 possible conditions (10 SOAs $\times$2 possible stimulus configurations) were presented pseudorandomly, once within each of the two blocks of 20 practice trials, and twice within each of the eight blocks of experimental trials.

3.2. Results

The proportion of 'vision first' responses was converted to its equivalent Z-score, and the intermediate eight SOAs were used to calculate a best-fitting straight line, just as in Experiment 1. The JND and PSS data (see Fig. 3 and Table 1 for a summary) were submitted to paired samples *t*-tests comparing the Same vs. Different Position conditions. Three participants were excluded from the subsequent data analysis because one or more of their PSSs were larger than 200 ms, which was beyond the range of SOAs tested. Once again, neither the analysis of the JND data [$t(7)=0.76$, $P=0.47$, n.s.], nor the analysis of the PSS data [$t(7)=0.51$, $P=0.62$, n.s.], revealed any significant difference in performance between the Same and Different Position conditions, replicating the null results of Experiment 1. The *t*-tests revealed that the observed PSS values were not significantly different from 0 ms in either the Same [$t(7)=0.90$, $P=0.40$, n.s.] or Different Position conditions [$t(7)=0.071$, $P=0.95$, n.s.].

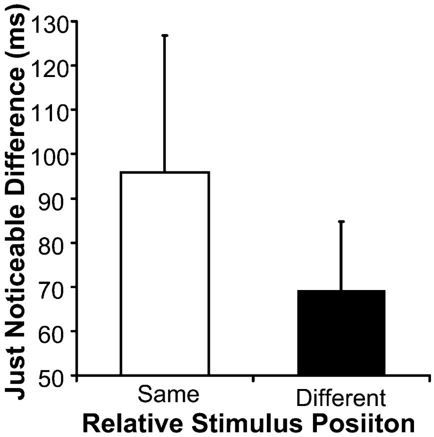

Fig. 3. Just noticeable differences (JNDs) for the two audiovisual stimulus pairs in Experiment 2. The errors bars represent the within-observer S.E. of the mean. This graph once again highlights the finding that audiovisual TOJ performance is not facilitated by presenting the stimuli from different locations, even when the location of the auditory stimulus was made unpredictable.

3.3. Comparison of the results of Experiments 1 and 2

We conducted between-experiments analyses of the results from Experiments 1 and 2 to assess

[3] The reverse prediction could also be made – namely that one would expect greater spatial redundancy effects under conditions where a unique spatial location is unambiguously associated with each sensory modality rather than when stimulus position is randomised as in our previous work (e.g. Spence et al., 2003; Zampini et al., in press). For it is only in the former situation that the location that was stimulated first provides a completely unambiguous cue as to which modality stimulus was presented first.

whether the degree of spatial uncertainty regarding the location (headphones vs. external loudspeaker) from which the auditory stimuli were presented (fixed presentation in Experiment 1 vs. random presentation in Experiment 2) had any effect on the precision with which participants could make multisensory TOJs. Analysis of the JND data using a mixed between-within ANOVA with the factors of Spatial Uncertainty (Fixed vs. Random presentation) and Relative Stimulus Position (Same vs. Different), revealed no significant main effects of Spatial Uncertainty [$F(1,17)<1.0$, n.s.] or Relative Stimulus Position [$F(1,17)<1.0$, n.s.], nor any interaction between these two factors [$F(1,17)<1.0$, n.s.]. A similar analysis of the PSS data did, however, reveal a main effect of Spatial Uncertainty [$F(1,17)=4.65$, $P<0.05$], demonstrating that the visual stimulus had to be presented significantly further in advance of the auditory stimulus for the two stimuli to be judged as occurring at the same time in the fixed presentation condition of Experiment 1 (mean PSS of 29 ms) than in the random presentation condition of Experiment 2 (mean PSS of 6 ms). There was no significant main effect of Relative Stimulus Position [$F(1,17)<1.0$, n.s.], nor interaction between the two factors in the analysis of the PSS data [$F(1,17)<1.0$, n.s.].

3.4. Discussion

Once again, the results of Experiment 2 revealed no modulatory effect of Relative Stimulus Position on the temporal precision with which participants could make multisensory TOJs. This result supports the view that it is not the unpredictability of stimulus location per se that accounted for the null effects reported in Experiment 1.[4] We will return to a fuller consideration of why the predictability of the location from which each stimulus modality was presented had so little effect in the multisensory TOJ studies reported here in the General Discussion.

The results of the first two experiments argue that the spatial confound proposed by Spence and colleagues (Spence et al., 2001, 2003) may not affect performance under all conditions. One critical difference between the present study and our previous experiments in this area is the use of headphone presentation for the auditory stimuli from different locations rather than two loudspeakers on either side of the midline. Two possibilities need to be considered here: first, stimuli presented over headphones may have a special status in the auditory system (cf. Buchtel et al., 1996). Alternatively, presenting all of the relevant stimuli from positions along the body midline may be qualitatively different from presenting stimuli from either side of the midline. In our previous experiments, the stimuli from different locations were processed, at least initially, by different cerebral hemispheres and this may be the critical factor in obtaining the advantage for different location stimuli (a point to which we return later).

Despite the lack of a significant main effect of Relative Stimulus Position in either Experiment 1 or 2, there was nevertheless a small numerical trend in the data toward better performance in the Different Position condition as compared to the Same Position condition (see Table 1). This raises the possibility that there might be some spatial redundancy effect present in these experiments that may simply have failed to reach significance because of the relatively small numbers of participants tested, and/or the smaller number of trials conducted in these studies as compared to our previous studies. While the null effect of Relative Stimulus Position reported in the combined analysis of Experiments 1 and 2 refutes this line of argument to some extent. (The next experiment, where the reverse numerical trend was reported, provides more compelling support for this null effect.)

There is another possible account for the apparently null effect of the Relative Stimulus Position factor reported in Experiments 1 and 2 — namely, that there might be a spatial redundancy effect, but that the facilitation of the precision of multi-

[4] The stimulus position could only be randomised in one modality in Experiment 2 (i.e. it is impossible to present lights from the same location as the headphones). One could argue, therefore, that the randomisation of stimulus position in both modalities might be a necessary prerequisite for participants not to direct their spatial attention to the front where the majority (2/3) of all stimuli (i.e. averaged across stimulus modality) were likely to occur (cf. Spence and Driver, 1996).

sensory TOJs attributable to the redundant spatial information in the Different Position (i.e. headphone presentation) condition might simply be negated if the temporal resolution for sounds presented over headphones was worse than that for sounds from fixation (cf. Spence et al., 2001). The possibility that these effects might serendipitously have cancelled each other out, thus resulting in the null overall effect of Relative Stimulus Position, cannot be ruled out on the basis of the experiments reported so far. Therefore, in Experiment 3, we attempted to address this issue directly by comparing performance for the Same and Different Position conditions for pairs of auditory and visual stimuli presented from two locations situated on the body midline and equidistant from central fixation. By using stimulus locations situated above and below fixation, we hoped to more closely match the perceptual acuity in the two conditions. We also doubled the number of experimental trials presented to each participant in this and in the following experiments to increase our statistical power as well. A null effect of spatial location in this new experiment would, therefore, support a crucial role for hemispheric redundancy in demonstrating an effect of Relative Stimulus Position.

4. Experiment 3

4.1. Methods

4.1.1. Participants

Thirteen right-handed participants (mean age of 24 years) took part in the experiment as paid volunteers, which took approximately 50 min to complete. The participants were naïve as to the purpose of the study, and none had taken part in any of the previous experiments reported here.

4.1.2. Apparatus, materials, design and procedure

The experimental situation was similar to Experiment 3 except that two LEDs (similar to the fixation LED used in Experiment 1) were placed 26 cm directly above and below the central fixation light, and at the same distance from the participant (i.e. 62 cm). A loudspeaker cone, similar to the external loudspeaker cone used in Experiments 1

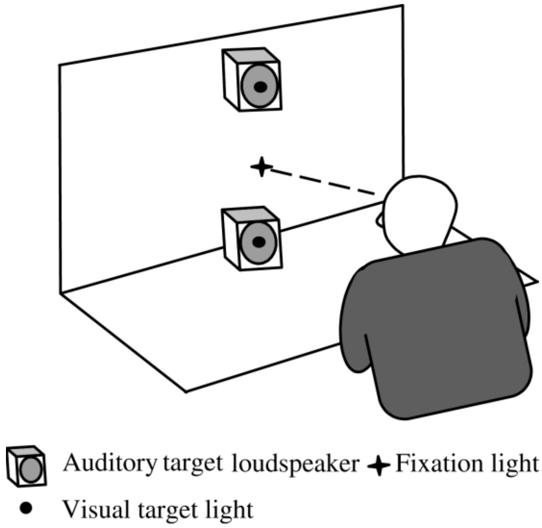

Fig. 4. Schematic view of the participant and the experimental setup used in Experiment 3. The dotted line shows the direction of fixation.

and 2, was placed directly behind each of these LEDs (see Fig. 4 for a schematic view of the participant and the experimental apparatus; note that headphone presentation of auditory stimuli was no longer used). Preliminary testing revealed that the participants experienced no difficulty in distinguishing between the auditory stimuli presented from the upper and lower loudspeakers. The Same and Different Position conditions were presented with equal probability within each block of experimental trials as in the previous experiment.

The experimental design and procedure was very similar to that used in Experiment 2 with the following exceptions. All participants now completed two blocks of 30 practice trials, followed by eight blocks of 80 experimental trials. The four possible stimulus combinations (upper sound and upper light, lower sound and lower light, upper sound and lower light and lower sound and upper light) were each presented pseudorandomly, 20 times within each block of experimental trials.

4.2. Results

The proportion of ‘vision first’ responses was converted to its equivalent Z-score, and the intermediate eight SOAs were used to calculate a best-fitting straight line. The JND and PSS data (see Fig. 5 and Table 1 for a summary) were submitted to paired samples *t*-tests comparing performance in the Same and Different Position conditions. Two participants were excluded from the subsequent data analysis because one or more of their PSSs were greater than 200 ms, which was beyond the SOA range tested. Once again, neither the analysis of the JND data [$t(10)=0.16$, $P=0.87$, n.s.], nor the analysis of the PSS data [$t(10)=1.53$, $P=0.15$, n.s.] revealed any significant difference between the Same and Different Position conditions, just as in the previous two experiments. The *t*-tests revealed that the observed PSS values were not significantly different from 0 ms in the Different Position condition [$t(10)=2.11$, $P=0.07$], nor in the Same Position condition [$t(10)=0.40$, $P=0.89$, n.s.].[5]

4.3. Discussion

Analysis of the results of Experiment 3 once again revealed a null effect of Relative Stimulus Position on the precision of audiovisual TOJs when the auditory and visual stimuli were presented from directly above and below central fixation, on the participant's midline. Perhaps more importantly, the small numerical trend toward JNDs in the Different Position condition being smaller than in the Same Position condition observed in Experiments 1 and 2 was now reversed in Experiment 3, with JNDs in the Same Position condition being slightly lower than in the Different Position condition (mean JNDs of 88 ms and 92 ms, respectively).

[5] We also investigated whether the stimuli positioned above and below the fixation point could influence the participant's performance per se. The JND data from Experiment 3 were submitted to a two-way within-participants ANOVA with the factors of Light Elevation (above vs. below fixation) and Relative Position (same vs. different). The analysis of the JND data revealed no main effect of Light Elevation [$F(1,9)=1.17$, $P=0.30$], nor of Relative Position [$F(1,9)=0.66$, $P=0.43$], nor any interaction between these factors [$F(1,9)=0.05$, $P=0.82$]. A similar analysis of the PSS data revealed no main effect of Light Elevation [$F(1,9)=1.51$, $P=0.25$] or Relative Position [$F(1,9)=0.75$, $P=0.41$], nor any interaction between these factors [$F(1,9)=0.02$, $P=0.89$].

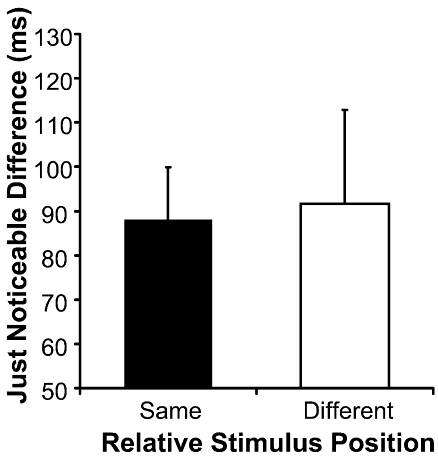

Fig. 5. Just noticeable differences (JNDs) for the two audiovisual stimulus pairs in Experiment 3. The errors bars represent the within-observer S.E. of the mean. The results show that when the auditory and visual stimuli were presented from upper and lower positions on the body midline, TOJ performance was no longer facilitated by the presence of redundant spatial cues.

The overall null effect of the Relative Stimulus Position factor demonstrated in Experiments 1 through 3 contrasts with significant effects reported in our previous studies (Spence et al., 2001; Zampini et al., in press). Having ruled out a number of other potential explanations for this null result (i.e. in terms of the degree of certainty regarding the locations from which stimuli were presented; in terms of the worse temporal resolution for sounds presented over headphones than when presented from fixation; and in terms of the smaller number of trials conducted possibly resulting in a loss of statistical power to detect a small effect), we are left with the most obvious remaining difference between the present Experiments 1–3, and our previous studies being whether or not the stimuli in the Different Position conditions were presented in different hemifields. In all of our previous experiments demonstrating a spatial redundancy benefit, the auditory and visual stimuli were placed in different hemifields in the Different Position conditions, whereas the auditory and visual stimuli were always presented on the midline no matter what the condition in the experiments reported here. Therefore, in the next experiment we attempted to demonstrate an effect of Relative Stimulus Position by presenting the auditory and visual stimuli from two locations, one situated to either side of fixation as in our previous work. Demonstrating a significant effect of Relative Stimulus Position here would suggest a critical role for hemispheric redundancy factors in modulating the 'spatial' redundancy effect. By contrast, another null result would hint at the existence of some other as yet unconsidered factor modulating performance in our multisensory TOJ experiments (cf. Frick, 1995).

5. Experiment 4

5.1. Methods

5.1.1. Participants

Ten right-handed participants (mean age of 26 years) took part in the experiment as paid volunteers. The experiment took approximately 50 min to complete. The participants were naïve as to the purpose of the study, and none had taken part in any of the previous experiments.

5.1.2. Apparatus and materials

The experimental setup was very similar to that in Experiment 3 with the exception that the two target LEDs and two target loudspeaker cones were now placed 26 cm to either side of the central fixation light, and at the same distance from the participant (62 cm; see Fig. 6 for a schematic view of the participant and apparatus). The experimental design and procedure was identical to that used in Experiment 3 with the exception that four possible stimulus combinations (sound left and light left, sound right and light right, sound left and light right and sound right and light left) were each now presented separately in different experimental blocks (i.e. a fixed stimulus location presentation paradigm was used, as in Experiment 1). This change in the design was incorporated in order to enable us to compare directly the results of the present experiment with those of Zampini et al. (in press) previous study. Zampini et al.'s study was identical to the present experiment with the sole exception that the four stimulus conditions were randomly intermingled within each experimental block of trials.

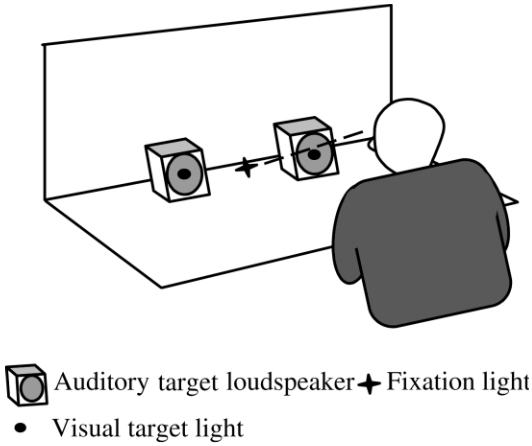

Fig. 6. Schematic view of the participant and the experimental setup used in Experiment 4. The dotted line shows the direction of fixation.

All participants in the present study completed two blocks of 30 practice trials, followed by eight blocks of 80 experimental trials. The order of presentation of the blocks was counterbalanced across participants. Participants were informed at the beginning of each block of trials about the presentation condition for that particular block of trials (i.e. both stimuli on the left; both stimuli on the right; auditory stimulus on the left and visual stimulus on the right; or auditory stimulus on the right and visual stimulus on the left).

5.2. Results

The proportion of 'vision first' responses was converted to its equivalent Z-score and the best-fitting straight line was calculated as in the previous experiments. Once again, the JND and PSS data (see Fig. 7 and Table 1 for a summary) were submitted to paired samples *t*-tests comparing the Same vs. Different Position conditions. The data from one participant were excluded from the analysis because one or more of their calculated PSSs fell outside the tested range. In contrast to the preceding three experiments, analysis of the JND data [$t(8)=2.09$, $P<0.05$] now revealed a signif-

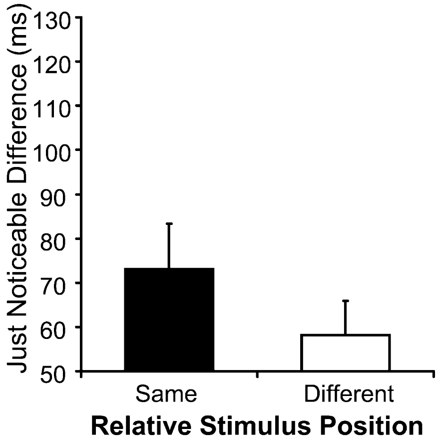

Fig. 7. Just noticeable differences (JNDs) for the two audiovisual stimulus pairs in Experiment 4. The errors bars represent the within-observer S.E. of the mean. The results highlight a significant difference in the accuracy of multisensory TOJs between the same and different position conditions.

icant difference between the Same and Different Position conditions (mean JNDs of 73 ms vs. 58 ms, respectively). A similar analysis revealed no significant difference between these two conditions in terms of the PSS data [$t(8)=1.17$, $P=0.28$]. The t-tests revealed that the observed PSS values were significantly different from 0 ms in the Different Position condition [$t(8)=3.40$, $P<0.01$], but not in the Same Position condition [$t(8)=1.80$, $P=1.11$, n.s.].

5.3. Between-experiments comparison of Experiment 4 and Zampini et al. (in press: Experiment 1)

We conducted between-experiment analyses to assess whether the difference between the fixed presentation in Experiment 4 and the randomised presentation incorporated in our previous study (Zampini et al., in press, Experiment 1) had any effect on the precision of multisensory TOJs. (Note that this comparison is analogous to that reported earlier between Experiments 1 and 2.) Analysis of the JND data using a mixed between-within ANOVA with the factors of Presentation (Fixed vs. Random) and Relative Stimulus Position (Same vs. Different) revealed a significant main effect of Relative Stimulus Position [$F(1,16)=16.96$, $P<0.01$] as expected, reflecting lower JNDs in the Different Position condition than in the Same Position condition (mean JNDs of 40 ms vs. 52 ms, respectively). More importantly, however, there was no significant main effect of Presentation [$F(1,16)<1.0$, n.s.], nor interaction between these two factors [$F(1,16)<1.0$, n.s.], thus showing absolutely no effect of target position uncertainty on the precision of multisensory TOJs, just as in our earlier comparison of the results of Experiments 1 and 2.

A similar between-experiments analysis of the PSS data revealed a significant main effect of Relative Stimulus Position [$F(1,16)=7.24$, $P<0.05$]. Visual stimuli had to be presented significantly further in advance of auditory stimuli for the two to be judged as occurring at the same time when they were presented from different positions (mean PSS of 61 ms) compared to when they were presented from the same location (mean PSS of 46 ms). No such result was found in the comparison between Experiments 1 and 2 (where all stimuli were presented on the midline), suggesting a possible role for interhemispheric transmission delays in determining the PSS when pairs of auditory and visual stimuli are presented to different cerebral hemispheres (cf. DeLacoste et al., 1985; Efron, 1963; Rugg et al., 1984; see also Mason and Geffen, 1996). There was no significant main effect of Presentation [$F(1,16)<1.0$, n.s.], nor any interaction between these terms [$F(1,16)<1.0$, n.s.], indicating that the target position uncertainty had no effect on the PSS.

5.4. Discussion

The most important finding to emerge from the analysis of Experiment 4 and the cross-experiment analysis was the significant reduction in temporal precision of multisensory TOJs observed when the different target modality stimuli were presented from the *same*, rather than from *different* positions. This result supports our previous findings regarding the beneficial effect of spatial redundancy on audiovisual and visuotactile TOJs (see Spence et al., 2001, 2003; Zampini et al., in press), at least when the stimuli in the Different Position condition are presented to either side of the participant's midline.

This spatial modulation of multisensory TOJs found in Experiment 4 contrasts with the lack of any difference between the Same and Different Position conditions reported in Experiments 1–3. One critical factor to be considered in understanding these contrasting results concerns the role of hemispheric effects (i.e. the use of different vs. the same cortical hemisphere). When the auditory and visual stimuli were placed across the body midline, each stimulus projected initially to a *different cerebral hemisphere* on trials where the two stimuli were presented from *different spatial locations*. By contrast, the two stimuli were projected to the same *cerebral hemisphere* when presented from the *same* spatial position. In other words, same vs. different position was perfectly confounded with same vs. different initial hemispheric projection in Experiment 4, and also in our previous research (Spence et al., 2001, 2003; Zampini et al., in press). By contrast, the presentation of all the stimuli directly on the body midline in Experiments 1–3 would have eliminated the contribution of any such hemispheric effects.

There are several possible explanations for why presenting stimuli to different cerebral hemispheres might have facilitated the accuracy of multisensory TOJs (see also Sherrick, 1968). Firstly, the activation of different hemispheres could make TOJs easier by providing redundant information regarding which position had been stimulated first, in addition to which modality appeared to have been presented first. If participants have access to such information, participants may have used which hemisphere was stimulated first to augment their ostensibly 'modality-based' TOJ judgments. No such hemispheric cues would have been present in the Same Position condition, and so TOJs would be expected to be less accurate. Secondly, more cerebral resources may be available to participants when each stimulus is processed by a different hemisphere (Banich, 1998; Kinsbourne and Cook, 1971; Kinsbourne and Hicks, 1978). According to both of the explanations outlined here, it should be easier to determine the temporal order of two events when they project (at least initially) to different cerebral hemispheres (as in the Different Position condition of Experiment 4 and our previous work) than when they project the same hemisphere.

In order to confirm this novel reinterpretation of the 'spatial' redundancy effect described in our previous work, we conducted a final experiment in which the auditory and visual stimuli were still horizontally displaced in the Different Position condition, but were now presented from within only the left or right hemispace (i.e. not crossing body midline). Given that both stimuli would now be presented within the same hemifield (and so project initially to the same cerebral hemisphere) we predicted that no main effect of Relative Stimulus Position would be found. By contrast, the demonstration of a significant spatial redundancy effect in this experiment would suggest the involvement of another, as yet unidentified, factor (perhaps related to the horizontal, rather than vertical, displacement of stimuli which might elicit some sort of lateralised response or orienting tendency on which participants could base their response).

6. Experiment 5

6.1. Methods

6.1.1. Participants

Eleven right-handed participants (mean age of 25 years) took part in this final experiment as paid volunteers. The experiment took approximately 50 min to complete. The participants were naïve as to the purpose of the study, and none had taken part in any of the previous experiments.

6.1.2. Apparatus, materials, design and procedure

The experimental situation was similar to Experiment 4 but now the two LEDs and two loudspeaker cones were placed on the left side of the central fixation point for six of the participants and on the right side for the remainder of the participants. Two LEDs were placed in one hemifield 15 and 67 cm from the fixation light (52 cm between them exactly as in Experiments 3 and 4), and at the same distance from the participant (62 cm). The two loudspeaker cones (also used in Experi-

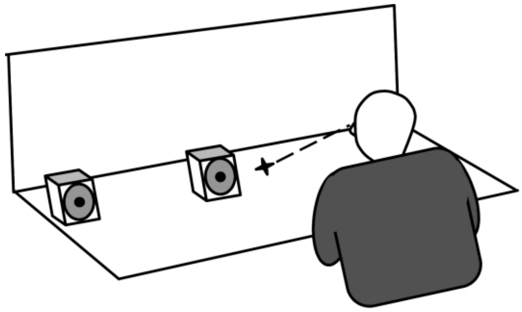

Fig. 8. Schematic view of the participant and the experimental setup used in Experiment 5. The stimuli could either be placed in the left hemispace (as shown in the figure) or in the mirror symmetrical location in the right hemispace (not shown). The dotted line shows the direction of fixation.

ment 4) were placed directly behind these LEDs to provide the auditory stimuli (see Fig. 8 for a schematic view of the experimental apparatus). The experimental design and procedure were exactly the same as in Experiments 3, with the exception of the variation in the location from which the stimuli were presented. Fixation was monitored as in previous experiments using the CCTV camera placed directly above and behind the fixation light that was placed directly in front of the participant.

6.2. Results and discussion

The proportion of 'vision first' responses was converted to its equivalent Z-score, and the intermediate eight SOAs were used to calculate a best-fitting straight line. The JND and PSS data (see Fig. 9 and Table 1 for a summary) were averaged over target side (i.e. left vs. right), and then submitted to a paired samples *t*-tests to assess the influence of Relative Stimulus Position (Same vs. Different). Four participants were excluded from the subsequent data analysis because one or more of their PSSs were larger than 200 ms, which was beyond the range of SOAs tested. As predicted, neither the analysis of the JND data [$t(6)=0.88$, $P=0.41$, n.s.], nor the analysis of PSS data [$t(6)=1.01$, $P=0.35$, n.s.] revealed any significant differences between the Same and Different Position conditions. It is interesting to note that the trend in this final experiment is toward the Same Position condition leading to lower JNDs than the Different Position condition. While it remains possible that this effect may have reached significance if we had tested a larger group of participants, the key point remains that this result contrasts with the opposite pattern of results reported in Experiment 4. The *t*-tests revealed that the observed PSS values were significantly different from 0 ms in the Different Position condition [$t(6)=2.81$, $P<0.05$], and marginally significant in the Same Position condition [$t(6)=2.28$, $P=0.06$].[6]

These results confirm the view that when the stimuli in the Different Position condition do not fall across the body midline (even if they are arrayed horizontally), then the Relative Stimulus Position factor has little effect on the precision of multisensory TOJs. This result supports the view that the apparent 'spatial' redundancy effect demonstrated in Experiment 4, and in several of our previous studies (Spence et al., 2001, 2003; Zampini et al., in press), should really be considered as a 'hemispheric' redundancy effect instead; for it is the presentation of stimuli to different cerebral hemispheres that is the critical prerequisite for improved performance in the Different Position condition, and not the introduction of a spatial displacement per se. Note that this contrasts with the interpretation given by Zampini et al. (in press) in terms of multisensory binding. However, taken together the evidence from the two studies seems

[6] In a further analysis, we also investigated whether the stimuli presented near to the fixation light might have been perceived preferentially (i.e. more rapidly and/or more saliently) than the stimuli presented further from fixation, hence influencing TOJ performance. One additional subject was excluded from this analysis because one of the data points had the PSS beyond the interval tested. The JND data from Experiment 5 were submitted to a two-way within-participants ANOVA with the factors of Light Position (near vs. far from fixation) and Relative Position (same vs. different). The analysis of the JND data revealed no main effect of Light Position [$F(1,5)<1.0$], nor of Relative Position [$F(1,5)<1.0$], nor any interaction between these factors [$F(1,5)<1.0$]. A similar analysis of the PSS data revealed no main effect of Light Position, nor of Relative Position, nor any interaction between these factors [all $Fs(1,5)<1.0$].

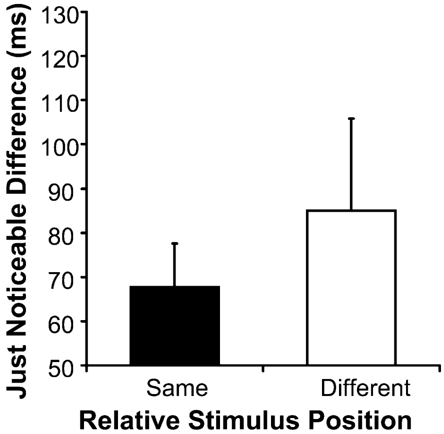

Fig. 9. Just noticeable differences (JNDs) for the two audiovisual stimulus pairs in Experiment 5. The errors bars represent the within-observer S.E. of the mean. The results once again show that when the audiovisual stimuli were both presented within the same hemifield, (i.e. not presented across the body midline) then performance was not facilitated by the presence of redundant spatial cues.

most consistent with the hemispheric redundancy account.

7. General discussion

The most important result to emerge from the analysis of the five experiments reported in the present study is that the introduction of a spatial discrepancy between the position of stimuli presented to different modalities does not, by itself, necessarily facilitate multisensory TOJ performance (i.e. it does not lower of JNDs; see Experiments 1–3 and 5). Instead, it appears that the accuracy of multisensory TOJs are improved only when the introduction of a spatial discrepancy leads to the stimuli being projected, at least initially, to different cerebral hemispheres (see Experiment 4; Spence et al., 2001, 2003; Zampini et al., in press; cf. Geffen and Quinn, 1984). The present results, therefore, suggest that the apparent 'spatial' redundancy effect identified in our previous research (see, for example, Spence et al., 2003) should actually be considered in terms of a hemispheric redundancy effect instead.

There are several possible reasons for why presenting the two stimuli to different cerebral hemispheres might facilitate TOJ performance, when compared to situations in which both stimuli project to the same hemisphere. Firstly, it may be that there are simply more cerebral resources available to process the two stimuli when they project to different hemispheres than to the same hemisphere. Many researchers have argued that each cerebral hemisphere can be considered to possess a somewhat separable pool of attentional resources (e.g. Banich, 1998; Friedman and Polson, 1981; Herdman and Friedman, 1985; Kinsbourne and Cook, 1971; Kinsbourne and Hicks, 1978; Passarotti et al., 2002). Therefore, one might expect that multisensory TOJs would be more accurate if each stimulus was initially processed by one of these separable pools of resources (e.g. in the Different Position condition of Experiment 4) than when they were both processed initially by the same hemisphere (e.g. in the Same Position condition of Experiment 4). Additionally, processing the two stimuli in different hemispheres might also be expected to reduce the possibility of confusion regarding which stimulus came first by increasing the 'functional cerebral distance' between sites of neural processing of the two stimuli within a highly-linked 'cerebral space' (see Kinsbourne and Cook, 1971; Kinsbourne and Hicks, 1978). Finally, if people have any sort of access to which hemisphere was stimulated first (perhaps related to some sort of primitive orienting response; Kinsbourne, 1987, 1993), then this might also provide a form of redundant information that participants could use to aid their judgments about which modality was presented first. Some support for this latter view comes from the fact that crossing the hands has been shown both to lead to errors in primitive orienting responses (e.g. Driver and Spence, 1998; Groh and Sparks, 1996) and also to the elimination of the Different Position redundancy effect demonstrated for pairs of visual and tactile stimuli (see Spence et al., 2003, Experiment 1).

Whatever the underlying mechanism of the hemispheric redundancy effect turns out to be, the point remains that our results suggest that prior research in which different modality stimuli were systematically presented from different sides of fixation (e.g. Teatini et al., 1976) most likely overestimated the genuine temporal precision with which their participants could make multisensory TOJs. However, the present results also suggest that those previous studies in which the auditory and visual stimuli were serendipitously presented on the midline (with auditory stimuli typically presented over headphones, and visual stimuli from near to fixation as in Experiments 1 and 2; e.g. Dinnerstein and Zlotogura, 1968; Hirsh and Sherrick, 1961; Jaskowski et al., 1990; Rutschmann and Link, 1964) may have provided more accurate values than has been recently suggested by Spence et al. (2003).[7]

The second major result to emerge from the analysis of the experiments reported in the present study was the finding that certainty regarding the location from which auditory and visual stimuli will be presented does not in itself facilitate multisensory TOJs when compared to a situation in which target position is uncertain. This null result was demonstrated both in the comparison of the first two experiments, when the location of auditory stimuli was either fixed (Experiment 1) or randomised (Experiment 2), and again in the comparison of Experiment 4 (where the position from which each modality was presented was entirely predictable) with a similar study conducted by Zampini et al. (in press) in which the location of both auditory and visual stimuli was randomised. These null results are somewhat surprising since knowledge of the location from which auditory and visual stimuli would be presented might allow participants to direct their endogenous auditory and visual spatial attention to that location throughout each block of trials (e.g. Driver and Spence, 1994; Spence and Driver, 1996) rather than having to divide their attention between both locations in both modalities. Given previous results from a range of different tasks, such a focusing of attention would be expected to facilitate the accuracy of multisensory TOJ performance. While the null results reported here might suggest that our participants simply found it too difficult to direct their auditory and visual attention in different directions simultaneously, it is important to note that Spence et al. (2001), (Experiment 4) also demonstrated little effect of directing visual and tactile spatial attention to either the left or right on the accuracy of visuotactile TOJs. Therefore, while directing spatial attention to a particular location may speed up the relative time of arrival of stimuli at the attended location (leading to a change in the PSS known as the 'prior entry' effect; see Spence et al., 2001) it seems to have little influence on the veridicality of multisensory TOJs (i.e. it has no effect on multisensory JNDs). This result contrasts with previous claims from studies of intramodal visual TOJs, where shifts of spatial attention were shown to lead to changes of both the PSS and the JND (e.g. Stelmach and Herdman, 1991; though see Spence et al., 2001). The suggestion of fundamental differences between intramodal and multisensory TOJs remains an interesting and important area for future research.

[7] We could not rule out the possibility of there being a small residual enhancement of multisensory TOJs in the headphone presentation (i.e. Different Position) condition situation, as suggested by the small numerical trends toward lower JNDs in this condition as opposed to the external loudspeaker (i.e. Same Position) condition reported in both Experiments 1 and 2.

Acknowledgments

Charles Spence and David I. Shore were funded by a Network Grant from the McDonnell-Pew Centre for Cognitive Neuroscience, University of Oxford. David I. Shore was also funded by an operating grant from the Natural Science and Engineering Council of Canada.

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