THE TEMPORAL WINDOW OF VISUOTACTILE INTEGRATION

THE TEMPORAL WINDOW OF VISUOTACTILE INTEGRATION: EXAMINATION OF SIMULTANEITY JUDGMENT AND TEMPORAL ORDER JUDGMENT TASKS

By

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Lay Abstract

Perception often involves the use of more than one sensory modality at the same time; for example, touching an object usually produces sensory signals in the visual and tactile modalities. Since the amount of time needed to transmit and process sensory signals is different among the modalities, the brain allows for a certain time difference between signals of various pairs of modalities that it will consider as coming from one event. Two tasks commonly used to measure these allowable time differences are the simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks. Although they are usually used interchangeably, the present data show that the results from these tasks in the visuotactile pairing of modalities are unrelated, and a major contributing reason appears to be that these tasks are not the most reliable.

Abstract

The simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks are the two widely used methods for measuring the window of multisensory integration; however, there are some indications that these two tasks involve different cognitive processes and therefore produce unrelated results. The present study measured observers' visuotactile window of integration using these two tasks in order to examine whether or not SJs and TOJs produce consistent results for this particular pairing of modalities. Experiment 1 revealed no significant correlations between the SJ and TOJ tasks, indicating that they appear to measure distinct processes in visuotactile integration, and in addition showed that both sensory and decisional factors contribute to this difference. These findings were replicated in Experiment 2, which, along with Experiment 3, also showed that the reliability of the SJ and TOJ tasks may in part be responsible for the lack of agreement between these two tasks. A secondary result concerned the point of subjective simultaneity (PSS), which were tactile-leading across all three experiments. This contradicts some of the previous literature in visuotactile integration. Manipulating the spatial distance between the visual and tactile stimulus (Experiment 2) and the certainty of stimulus location (Experiment 3) did not lead to significant changes of the location of the PSS.

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List of Abbreviations

SJ: simultaneity judgment task

TOJ: temporal order judgment task

SOA: stimulus onset asynchrony

PSS: point of subjective simultaneity

ms: millisecond

Declaration of Academic Achievement

The development of Experiment 1, including setting the overall goal of the present research project based on the data of this experiment, was accomplished through discussion amongst myself, David Shore, and Yi-Chuan Chen. Experiments 2 and 3 were developed through discussion between myself and David Shore. David Shore and Miroslav Cika helped with the set-up of the experimental apparatus.

Experiment 1 was programmed by Yi-Chuan Chen. Experiments 2 and 3 were programmed by myself, with the help of David Shore. Data collection was completed by myself (all 3 experiments) and with the help of Greg Byun (Experiments 2 and 3) and Kathy Jiang (Experiment 3). Data analysis was completed by myself.

Introduction

Reaching out and touching an object often produces sensory signals in both the visual and tactile modalities. Our perception, which typically consists of a single percept (Ernst & Bülthoff, 2004), therefore requires a mechanism of multisensory integration (Driver & Spence, 2000). Differences in transmission and transduction latencies for the different senses present a problem for the perceptual system (Spence & Squire, 2003; Vroomen & Keetels, 2010). In order to overcome this challenge, the brain adopts, and can dynamically recalibrate, a relatively wide window of integration[1], or temporal binding window, within which the observer perceives the two stimuli (one in each modality) as coming from the same event. Measuring this window of integration has a long history within experimental psychology (Mollon & Perkins, 1996; Spence et al., 2001), and forms a fundamental question for the present paper.

Two methods have been used across the literature—the simultaneity judgment (SJ) task, and the temporal order judgment (TOJ) task. In both tasks, the observer is presented with two stimuli, one to each modality, at varying stimulus onset asynchronies (SOAs). In the SJ task observers report if the two stimuli appeared to be simultaneous or not, whereas in the TOJ task observers report which of the two stimuli came first. For both tasks, one can determine the perceived point of subjective simultaneity (PSS; the SOA at which the participant is most likely to perceive two stimuli as occurring at the same point in time), as well as the sensitivity or just noticeable difference (JND; the smallest time interval

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[1] There is some evidence to suggest that the window of integration may be distinct from the perception of simultaneity (e.g. Fujisaki & Nishida, 2010; Soto-Faraco & Alsius, 2009). Some researchers may therefore refer to this window as the "simultaneity window".

between two stimuli for participants to be able to reliably notice that they were presented at different points in time). The sensitivity is often considered an approximation of the size of the window of integration. Hirsh and Sherrick (1961) had reported that the size of the visuotactile temporal binding window was approximately 20 ms, but more current research have discovered that this estimate can be affected by a wide variety of factors, such as whether the stimuli were presented from one or two locations (Spence et al., 2001), the posture adopted by the observer (Spence et al., 2003), and the age of the observers (Poliakoff et al., 2006).

Throughout the literature, both tasks are assumed to provide a reliable index of the window of integration; however, there have been some indications that different mechanisms are involved in these two tasks. With audiovisual stimuli, no significant correlations were obtained between measures from SJ and TOJ tasks, indicating that they may represent distinct perceptual processes in audiovisual integration (van Eijk et al., 2008[2]; Love et al., 2013). With unimodal tactile stimuli, crossing the hands across the midline results in increased difficulty of judging temporal order (i.e. the crossed-hands deficit) in the TOJ task (Shore et al., 2002), but no deficit using the SJ task (Axelrod et al., 1968; Geffen et al., 2000). Recently, neuroimaging data has also revealed additional areas of activation in the the brain during TOJs that were not observed during the SJ task (Binder, 2015), suggesting an increased cognitive effort for encoding the temporal order of the two stimuli. Perhaps the most interesting results come from the temporal

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[2] This study also included the SJ3 task, where participants either indicated which of the two stimuli was presented first, or that the two stimuli occurred simultaneously. The results from this task were highly correlated with those from the present SJ task, and since it is not used in the current study, it will only be discussed briefly throughout this paper as needed.

recalibration literature: changes in the window of integration, as a result of exposure to systematic time lags between the two stimuli differed between SJ and TOJ in some experiments (e.g. Vatakis et al., 2008; Fujisaki et al., 2004 vs. Vatakis et al., 2008) but not others (e.g. Takahashi et al., 2008 vs. Keetels & Vroomen, 2008; Fujisaki et al., 2004 vs. Harrar & Harris, 2008). These results bring into question the assumption that both tasks measure the same integration window.

In order to investigate the underlying causes of such differences between the SJ and TOJ tasks, two major goals were developed for the present study. First, we measured visuotactile integration using the SJ and TOJ tasks in an effort to determine whether or not they will produce consistent results, and if so, the possible factors that are responsible for these task differences. There have been few studies in the literature that had specifically aimed to test the relation of the SJ and TOJ tasks in the visuotactile pairing of modalities. Fujisaki and Nishida (2009) used the two tasks to measure the temporal resolution (which is inversely proportional to the width of the window of integration) of four stimulus combinations, one of which was visuotactile. They observed an overall difference in the estimates of the visuotactile temporal resolution between SJ and TOJ; however, specific statistical comparisons were not provided and it is uncertain whether this was a significant difference. Machulla et al. (2016) reported a nonsignificant PSS correlation between the visuotactile SJ and TOJ tasks; the correlation for the estimates of sensitivity was only marginally significant. They were unable to elaborate on the reasons for the lack of correlations due to the fitting method they had used. The present paper addresses some of these concerns.

The second major goal of this study was to examine the reliability of the SJ and TOJ tasks, and how this factor may contribute to the discrepancies between the two tasks observed in the literature. Few studies have reported whether these tasks produce consistent results when the same observers repeat the measurements. Love et al. (2013) tested observers on audiovisual SJ and TOJ tasks using multiple types of stimuli for each task. TOJ tasks produced higher correlations with the PSS measurement, while the SJ tasks showed higher correlations with the measure of sensitivity. This appears to indicate that observers' PSS values remained constant or changed consistently among stimuli types when measured with the TOJ task, and the same was true for the sensitivity when measured with the SJ task. In other words, each task appears to provide more reliable estimates for one of the two parameters relative to the other task. García-Pérez & Alcalá-Quintana (2012) used simulated data to examine the data fitting procedure itself, in terms of whether estimated parameter values obtained from fitting the data agreed with the true parameter values. Estimates of the sensitivity were somewhat more accurate in the SJ task relative to the TOJ task, which may indicate that it is more difficult to estimate the sensitivity using TOJs. Estimates of reliability are critical since if the tasks do not produce dependable estimates within themselves, then examining the relation between the tasks is seriously compromised.

To compute estimates of our observers' PSS and sensitivity, we used a recently developed independent-channels model (García-Pérez & Alcalá-Quintana, 2012), which, in estimating these two perceptual parameters, also considers sensory processing as well as response decisions. Its ability to estimate these additional parameters provides an advantage over fitting experimental data using arbitrary functions, such as the Gaussian or logistic functions, as had been done previously (e.g. Zampini et al., 2005a; Harrar & Harris, 2008; van Eijk et al., 2008; Fujisaki & Nishida, 2009; Love et al., 2013; Linares & Holcombe, 2014). Apart from determining the PSS and sensitivity, the parameters in these types of arbitrary functions usually do not carry any meaning in relation to the sensory processing and decisional aspects of observers' judgments, which seem to be critical factors in evaluating the underlying mechanisms of why the two tasks may differ. In addition, Alcalá-Quintana and García-Pérez (2013) argue that the smoothness of Gaussian and logistic functions do not truly reflect observers' experimental data, which are often asymmetric and irregular, whereas independent-channels models more adequately describe these aspects of the empirical data (see also García-Pérez & Alcalá-Quintana, 2015 for a meta-analysis of recent studies using their model).

A third goal for the present paper arose during data collection. Based on the results listed in Table 1 and the relative transduction times for visual and tactile stimuli, we expected that visual stimuli would require more time to be processed and therefore must be presented first for simultaneity to be perceived (Vroomen & Keetels, 2010). However, this is clearly not always the case as researchers have reported both vision-leading as well as tactile-leading PSS values. In the present study, we test two hypotheses that may explain the tactile-leading PSS values reported by some studies. One factor that appears to play a role is the phenomenon of *prior entry*—attended stimuli are processed faster than unattended stimuli (Titchener, 1908; see also Shore et al., 2001; Spence et al., 2001; Schneider & Bavalier, 2003; Zampini et al., 2005b; see Spence & Parise, 2010 for a review). Within this context, observers may have implicitly attended to vision over touch (cf. Posner et al., 1976), which would produce a tactile-leading PSS; we were interested in whether equalizing the amount of attention that observers directed toward the two modalities (i.e. reducing the amount of prior entry for vision) would shift the PSS towards vision-leading. A second factor that may be critical in producing a vision-leading PSS is the spatial certainty of stimulus presentation: many studies that had reported a vision-leading PSS presented each stimulus from two locations in space (e.g. Spence et al., 2001; Spence et al., 2003; Poliakoff et al., 2006; Finkelshtein, 2015), while tactile-leading PSS values have been reported from those that had presented each stimulus from one location (Noel et al., 2015; Van de Burg et al., 2015). Thus, in the final experiment, we investigated the impact of spatial uncertainty on the PSS.

Scope of the Present Study

The primary aim for the present experiments was to investigate whether or not the SJ and TOJ tasks provide consistent results when measuring timing judgments for the visuotactile pairing of modalities, and to identify possible reasons if their results do not agree. Specifically, we are interested in examining both the sensory and decisional differences when observers make SJs and TOJs, as well as whether the tasks themselves produce reliable measurements. In both tasks, observers were presented with two stimuli separated by various onset intervals; in SJ, they judged whether the two stimuli occurred simultaneously, and in TOJ, they judged which of the two stimuli occurred first. We were interested in comparing two key performance measures obtained from the two tasks: the point of subjective simultaneity (PSS) and the sensitivity. The PSS indicates the amount of time one stimulus must lead the other for simultaneity to be perceived. The estimated sensitivity is an approximation of the size of the window of integration, within which observers will reliably perceive simultaneity.

A secondary goal was to examine two factors that may affect the PSS specifically: prior entry (cf. Spence et al., 2001) and spatial uncertainty. Given a bias to attend to the visual modality (Posner et al., 1976), a tactile-leading PSS could be observed unless care is taken to equate attention to the two modalities. Experiment 2 attempted to equalize the amount of attention directed towards the two modalities. Experiment 3 manipulated the spatial certainty of stimulus location (see Table 1) to test for shifts of the PSS. Across all three experiments, participants completed both the SJ and TOJ task and correlations were conducted both between the two tasks and within each task on both measures of PSS and sensitivity.

Table 1: selection of visuotactile PSS and sensitivity values from previous studies, with standard error in parentheses where reported. Positive PSS values indicate that they were located on the vision-leading side. *VL = visual left; VR = visual right; TL = tactile left; TR = tactile right; SS = same side; DS = different sides.*

Study	No. of partici-pants	Method of stimulus presentation	Judgment task	Reported PSS (ms)	Reported sensitivity (ms)
Spence, Shore, & Klein (2001)		Two locations each for the visual (LEDs) and tactile (vibrations) stimulus			
Experiment 1A (divided attention)	16		TOJ, VL-TL	-4.7 (9.2)	59.1 (5.2)
			VR-TR	33.3 (14.9)	76.6 (5.9)
			VL-TR	28.1 (8.8)	36.6 (3.0)
			VR-TL	26.4 (6.1)	36.6 (3.2)
			TOJ, VL-TL	5.5 (13.9)	76.1 (11.7)
Experiment 3A (attend left)	12		VL-TR	-9.3 (20.9)	59.0 (9.6)
			VR-TL	65.7 (21.8)	67.9 (10.0)
			TOJ, VR-TR	13.5 (8.6)	86.5 (12.8)
Experiment 3B (attend right)	12		VL-TR	24.7 (17.2)	64.3 (12.0)
			VR-TL	29.2 (12.0)	56.5 (8.4)
Experiment 4 Divided attention	13		TOJ, VL-TL	-13.2 (15.2)	74.1 (7.3)
			VR-TR	10.8 (12.8)	78.7 (7.3)
			VL-TR	20.1 (11.7)	68.4 (6.1)
			VR-TL	33.1 (10.3)	65.7 (5.0)
			TOJ, VL-TL	-11.2 (15.4)	77.9 (6.2)
			VL-TR	-3.2 (10.6)	66.0 (4.0)
Attend left	13		VR-TL	85.0 (22.6)	95.6 (13.7)
			TOJ, VR-TR	-6.7 (11.5)	79.3 (10.2)
			VL-TR	49.0 (10.2)	69.6 (8.3)
Attend right	13		VR-TL	3.2 (12.5)	65.6 (6.7)
Spence et al. (2003)		Two locations each for the visual (LEDs) and tactile	TOJ (un-crossed hands)		
Experiment 1	10		SS	10.15 (7.5)	

		(vibrations) stimulus	DS	23.73 (10.0)	
Poliakoff et al. (2006)		Two locations each for the visual (LEDs) and tactile (vibrations) stimulus, presented from two LEDs and two vibrators at each location	TOJ		
	16 young		SS	~40	105
			DS	~40	99
	11 elderly		SS	-18	155
			DS	~40	118
Keetels and Vroomen (2008)	10	One location each for the visual (LED) and tactile (vibration) stimulus, presented close together	TOJ; exposure lag of 0 ms	8.6 (7.2)	32.3 (1.3)
Takahashi et al. (2008) Experiment 2	8	Visual and haptic deformation	SJ; exposure lag of 0 ms	20.3	
Fujisaki and Nishida (2009)	7	One location each for the visual (computer screen flash) and tactile (finger tap) stimulus	SJ	Tactile-leading	~55
			TOJ	Vision-leading (estimated; specific values not reported)	~30
Finkelshtein (2015)		Two locations each for the visual (LEDs) and tactile (vibrations) stimulus	TOJ		
Chapter 2, Experiment 1	16		SS	13.6 (4.6)	115.3 (2.8)
			DS	30.6 (4.6)	92.2 (2.8)
Noel et al. (2015)	18	One location each for the visual	SJ	-73.41 (5.25)	136.04 (14.71)

		(computer screen flash) and tactile (vibration via speaker) stimulus			
Van de Burg et al. (2015)	18	One location each for the visual (computer screen flash) and tactile (vibration via speaker) stimulus	SJ	Tactile-leading (specific value not reported)	
Machulla et al. (2016)	11	One location each for the visual (LED) and tactile (vibration) stimulus, presented close together	SJ TOJ	-10 (10) 46 (16)	65 (6) 55 (6)

Experiment 1

Method

Participants

Seventeen participants (8 males, 9 females; mean age = 19 years, range = 17 to 21 years) were tested in both the SJ and TOJ tasks. All were undergraduate students at McMaster University participating in exchange for course credits. All participants had normal or corrected-to-normal vision as confirmed by visual screening tests prior to the start of the experiment (20/20 vision on the Lighthouse eye chart, a minimum score of 40 arcsec on the Randot® test of stereoacuity, sees four dots on the Worth 4 Dot test). In addition, all were predominantly right-handed as determined by a handedness questionnaire. Written consent was obtained from all participants, who remained naïve as to the purpose of the study. Four additional participants were tested but excluded because they identified as being predominantly left-handed (1 participant) or performed as outliers (3 participants—see inclusion criteria in Results). The study was approved by the McMaster University Research Ethics Board.

Apparatus and Stimuli

Participants were seated in a dimly-lit room with their head on a chin rest located 50 cm from the computer screen on which the visual stimuli were presented. A gray ring (2° inner diameters) in the center of a black background was displayed on the screen during the experiment. The visual stimulus was a 2° white disc presented in the middle of the gray ring with a duration of 16.7 ms (1 frame at the 60 Hz refresh rate). The tactile stimulus was presented via a rectangular tactile machine, which was placed on the table between the participant and the computer screen. Participants rested their right index finger on an opening above a small metal probe, which protruded upward when presenting the tactile stimulus, felt as a finger tap. The duration of each tap was also 16.7 ms. Throughout each of the two tasks, participants listened to white noise presented through headsets in order to mask the sounds produced by the tactile machine. Presentation of the stimuli was controlled by Matlab (MathWorks Inc., Natick, MA) and Psychtoolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007).

Design

Fifteen SOAs (±500, ±400, ±300, ±200, ±150, ±100, ±50, and 0 ms) were tested in the SJ task, while 14 SOAs (±500, ±400, ±300, ±200, ±150, ±100, and ±50 ms) were tested in the TOJ task. The 0 ms SOA was not included in TOJ as it would not make sense to judge temporal order if the two stimuli occurred simultaneously (i.e. there would be no correct response). Negative values indicate that the tactile stimulus was presented first, whereas positive values indicate that the visual stimulus was presented first. Each SOA was tested twice per block and all participants completed ten blocks for each task. A short break was permitted between blocks as well as between the two tasks. Eight participants first completed SJ, while the remaining nine participants first completed TOJ. The entire experiment typically took one hour to complete.

Procedure

Participants were instructed that during each trial of the experiment, a flash would be presented on the computer screen and a finger tap presented via the tactile machine. In the SJ task, participants were asked to respond orally "same" if they perceived that the visual and tactile stimuli were presented at the same time, or "different" if they perceived that the two stimuli were presented at different times. In the TOJ task, participants were asked to respond "flash" if they perceived that the visual stimulus was presented first, or "tap" if they perceived that the tactile stimulus was presented first. An experimenter sat beside the participant and keyed the responses into the computer.

Three separate practice blocks were completed prior to the start of the main experiment of each task. The first practice block consisted of eight trials: four with 0 ms SOA and one each of ±500 and ±300ms SOA in SJ, and two each of ±500 and ±300 ms SOA in TOJ. The purpose of this first block was to ensure that participants understood the experimental procedure and was therefore completed without the use of white noise via headsets. A minimum of 85% accuracy (i.e. at most one error) was required in order to proceed. The second practice block was identical to the first practice block, except that participants began to listen to white noise at this stage. The third practice block consisted of one trial for each SOA used in the task (15 SOAs for SJ, 14 for TOJ) and was designed to familiarize participants with the level of difficulty of the main experiment. There were no accuracy requirements for this final practice block.

Results

In order to ensure that participants remained focused and made a satisfactory level of effort throughout the experiment, those who remained in the final sample were required to meet the following inclusion criteria For SJ, 1) the proportion of "simultaneous" responses at the ±500 ms SOA was lower than the mean plus two standard deviations (SD) of all participants at that SOA, and 2) the proportion of "simultaneous" responses at the 0 ms SOA was higher than the mean minus two SD of all participants at that SOA. For TOJ, 1) the proportion of "visual-first" responses at the -500 ms SOA was lower than the mean plus two SD of all participants at that SOA, and 2) the proportion of "visual-first" responses at the +500 ms SOA was higher than the mean minus two SD of all participants at that SOA. Participants who did not meet the inclusion criteria for either task were excluded from both tasks. Seventeen participants remained in the final analyses.

The proportions of "simultaneous" responses in SJ for each participant at each SOA, as well as the overall mean proportions, are shown in Figure 1a. Similarly, the proportions of "visual-first" responses in TOJ for each participant at each SOA, as well as the overall mean proportions, are shown in Figure 1b. The overall mean proportions for SJ and TOJ are collectively shown in Figure 1c to illustrate observable differences between the two tasks. The data of each task were separately submitted to a three-way analysis of variance (ANOVA) with between-subject factors of task order (SJ vs. TOJ first) and sex and a within-subject factor of SOA; no effects of task order were found (SJ: $F(1, 13) = 1.99$, $p = .18$; TOJ: $F(1, 13) = 2.68$, $p = .13$). Males and females did not perform differently on the SJ task ($F(1, 13) = .48$, $p = .50$), but there was an overall difference in TOJ ($F(1, 13) = 9.68$, $p < .01$)[3].

Estimated parameters of the SJ and TOJ tasks

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[3] The sex difference statistic is included for reference purposes, but since within-task results were inconsistent across the three experiments presented in this paper, this difference is not discussed further.

Individual data for the SJ and TOJ tasks were separately fitted with the R routines reported in Alcalá-Quintana and García-Pérez (2013)[4], which were derived from an independent-channels model for describing stimulus timing judgment tasks proposed in García-Pérez and Alcalá-Quintana (2012). This model presumes that the peripheral processing times of the "test" and "reference" stimulus are accounted for by an exponential distribution, where the parameters λ_i and τ_i are respectively used to represent the processing speed and processing delay of these two stimuli. In the present study, the visual stimulus represents the "reference" stimulus and the tactile stimulus the "test" stimulus, whose time of presentation was varied with respect to the reference. The model thus estimates the processing speed for both the visual (λ_V) and the tactile (λ_T) stimulus, as well as the difference in processing delay between these two stimuli ($\tau = \tau_T - \tau_V$); these estimates are then used in a bilateral exponential distribution to describe the arrival time difference between the two stimuli at the central mechanism, which in turn guides the participant's response decision for each given trial. The resolution parameter δ represents the participant's ability to distinguish small SOAs between the visual and tactile stimulus such that simultaneity is perceived when the arrival time difference is within $\pm\delta$ (i.e. it is the threshold of simultaneity). δ is therefore proportional to the window of integration: a large (small) δ value indicates a wider (narrower) window. In SJ, the response error parameters ε_{VF}, ε_{TF} and ε_S respectively represent the probabilities of misreporting (e.g. key responses errors) a visual- or tactile-first trial as simultaneous, or a simultaneous trial

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[4] When using the R routines for fitting SJ and TOJ data (Alcala-Quintana & Garcia-Perez, 2013), the starting values for each parameter need to be provided by the user. Here are the starting values used to fit the data in the present study: LamBounds = [1/200 1/3]; TauBounds = [-Inf Inf]; DeltaBounds = [0 Inf]; LamTStart = [1/70 1/10]; LamRStart = [1/70 1/10]; TauStart = [-70 70]; DeltaStart = [20 150]; ErrStart = [0.05]; BiaStart = [0.5]; Model = 1.

as not simultaneous. In TOJ, there are only ε_{VF} and ε_{TF}, where ε_{VF} represents the probability of reporting a visual-first trial as tactile-first, and vice versa for ε_{TF}. Finally, an additional response bias parameter ξ is included for TOJ to represent the probability that a participant decides to respond "visual-first" when they cannot tell whether the visual or tactile stimulus was presented first (i.e. when the arrival time difference is within $\pm\delta$).

Individual PSS and sensitivity values were determined from the fitting procedure as follows. In SJ, the PSS was located at the midpoint between the two SOAs where the probability of responding "simultaneous" is 50% (the simultaneity boundaries). Sensitivity is represented by the parameter δ, which in our analyses corresponds well with the half-width of the simultaneity boundaries. In TOJ, the PSS is the SOA at which there is equal likelihood (i.e. 50%) of reporting visual- or tactile-first. Sensitivity is also represented by δ (which is estimated separately from SJ in the fitting procedure), and generally corresponds to the half-width between the SOAs where the probability of responding "visual-first" is 25% and 75% (i.e. the typical definition of the JND). We opted to use δ to represent the sensitivity for both SJ and TOJ, rather than the common definition of JND for TOJ, as it is a shared parameter in the model itself, as opposed to deriving the sensitivity values using different methods after fitting the data.

The mean PSS was negative for both SJ and TOJ (for individual participants, only one PSS was positive in SJ while five were positive in TOJ), indicating a tactile-leading requirement for simultaneity perception. One-tailed *t* tests verified that the PSS was significantly less than zero in both SJ ($t(16) = -4.18$, $p < .01$) and TOJ ($t(16) = -2.57$, $p = .01$). Repeated measures ANOVAs conducted among PSS and sensitivity estimates showed that there was no significant difference for PSS between SJ and TOJ ($F(1, 16) = 1.3$, $p = .27$) but participants showed higher sensitivity in the TOJ task ($F(1, 16) = 7.93$, $p = .01$).

Further repeated measures ANOVAs revealed that there was no significant difference in tactile processing speed (λ_T; $F(1, 16) = 1.13$, $p = .30$) nor the processing delay difference (τ; $F(1, 16) = .17$, $p = .69$) between SJ and TOJ, but the visual processing speed (λ_V) was significantly faster in SJ ($F(1, 16) = 9.25$, $p < .01$). In addition, nonsignificant differences between λ_T and λ_V in each task indicate that the processing speed of neither the visual or the tactile stimulus were faster compared to the other (SJ: $F(1, 16) = 1.87$, $p = .19$; TOJ: $F(1, 16) = .007$, $p = .93$). The mean τ in both SJ and TOJ were positive, suggesting that the visual stimulus arrived first at the central mechanism when both stimuli were presented simultaneously; however, the means were not significantly greater than zero in either task (SJ: $t(16) = 1.16$, $p = .13$; TOJ: $t(16) = .38$, $p = .35$). Although the error parameters (ε) between SJ and TOJ cannot be compared directly, we note that the proportion of instances where ε was needed to fit the participants' data was higher in TOJ (74%) than SJ (45%); participants therefore appear to be more error-prone in TOJ. The response bias (ξ) in TOJ was significantly greater than chance level ($t(16) = 2.11$, $p = .03$), indicating that participants were more likely to respond "visual-first" when they were uncertain of the temporal order. The mean and standard error of all the parameters from the fitting procedure are shown in Table 2.

Finally, correlations between SJ and TOJ were calculated in terms of the PSS and sensitivity measurements, and are shown in Figure 2. Nonsignificant correlations for both the PSS ($r = .25$, $p = .33$) and sensitivity ($r = -.15$, $p = .56$) suggest that the two tasks do not provide related results for the same group of participants. These results were verified using a bootstrapping procedure, where correlations between SJ and TOJ were calculated for 17 randomly selected subjects with replacement, and repeated over 10,000 trials. The mean of the distributions obtained from this procedure was approximately $r = .25$ for PSS and $r = -.14$ for the sensitivity, and in both cases $r = 0$ (i.e. no correlation) was within the 95% confidence interval of the frequency distribution.

Figure 1a: proportion of "same" (simultaneous) responses plotted against SOA; blue line represents mean proportions across all participants. Error bars represent standard error of the mean at each SOA.

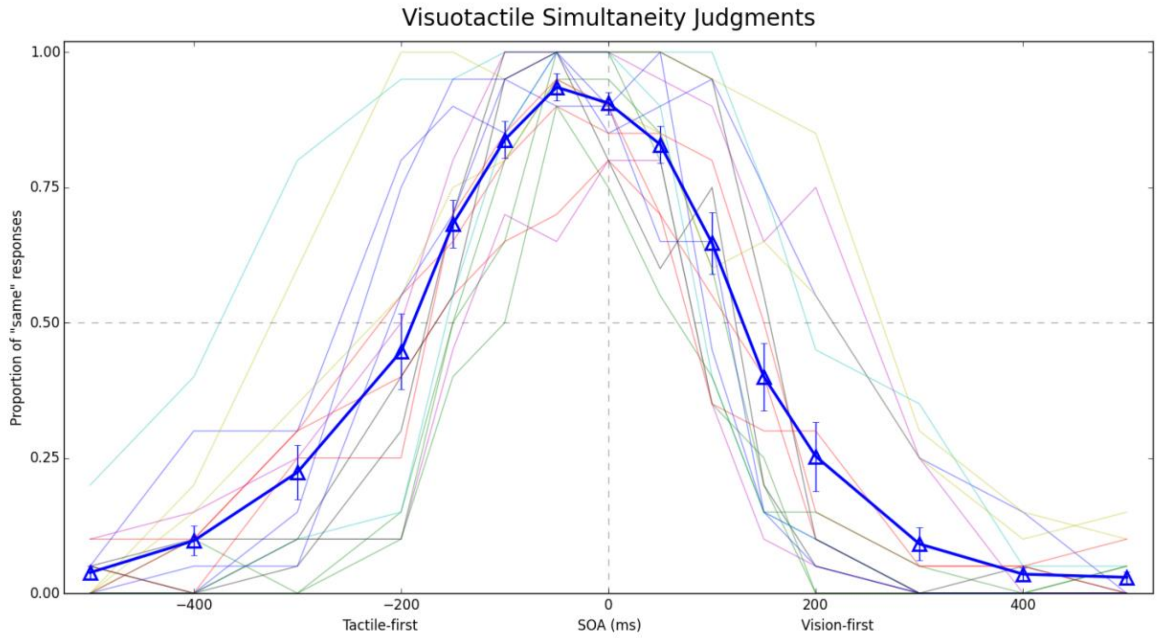

Figure 1b: proportion of "visual first" responses plotted against SOA; blue line represents mean proportions across all participants. Error bars represent standard error of the mean at each SOA.

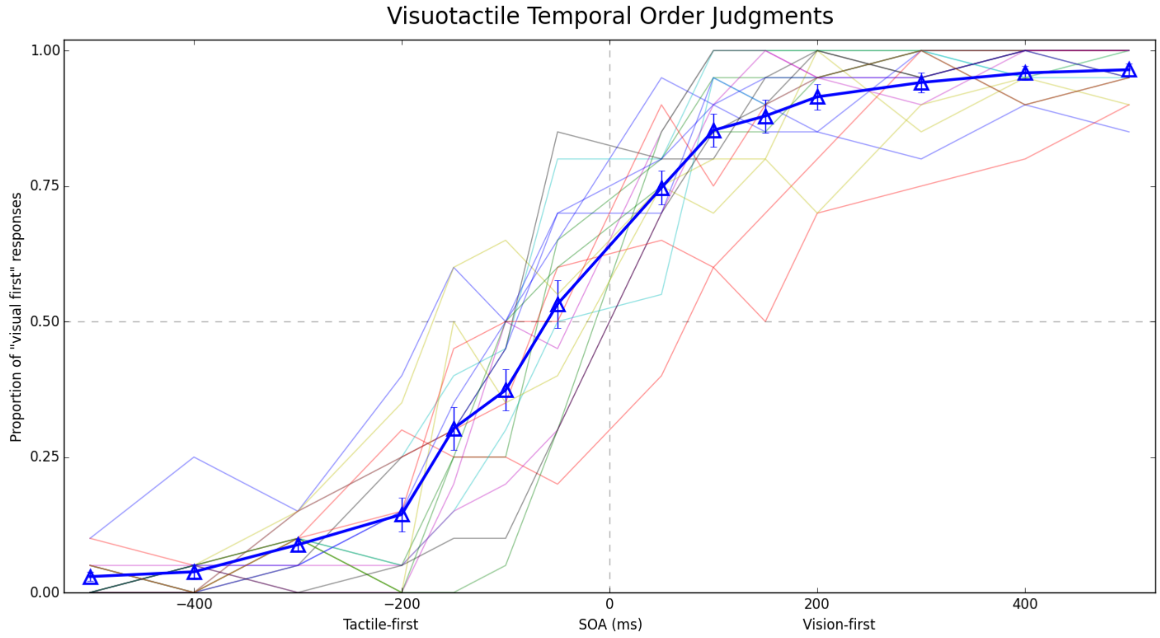

Figure 1c: mean proportions of "same" and "visual-first" responses in SJ and TOJ across all participants. Error bars represent standard error of the mean at each SOA.

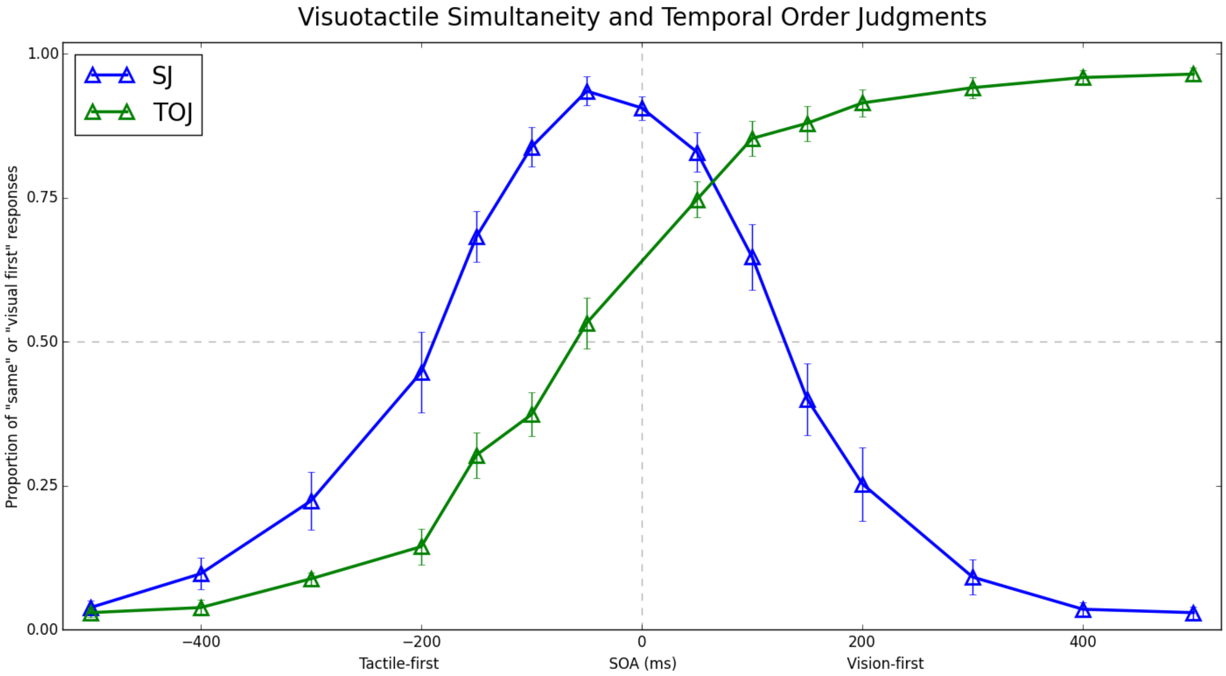

Figure 2: correlation of PSS and sensitivity between SJ and TOJ

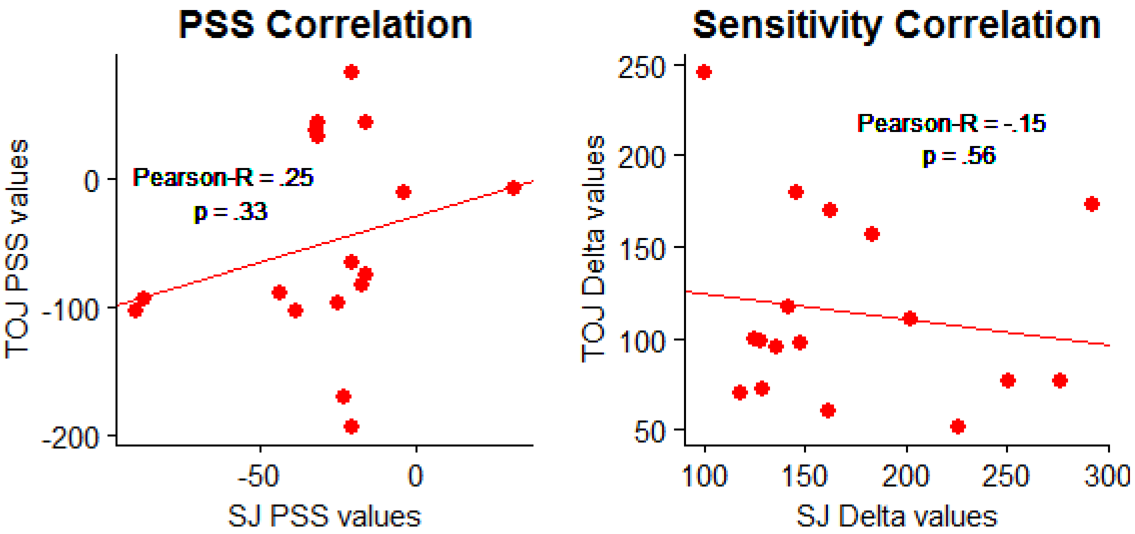

Table 2: mean and standard error of the estimated parameters from Experiment 1. Negative PSS values indicate that they were located on the tactile-leading side.

	SJ		TOJ	
	Mean	SE	Mean	SE
PSS	-28.33	6.25	-49.79	17.86
λ_V	.061	.023	.170	.034
λ_T	.058	.023	.106	.029
τ	16.60	13.16	6.98	16.83
δ	171.95	12.91	114.65	11.77
ε_{VF}	.028	.009	.043	.011
ε_{TF}	.041	.012	.031	.009
ε_S	.019	.012	-	-
ξ	-	-	.596	.042

Discussion

Experiment 1 measured the magnitude of observers' visuotactile window of integration using the SJ and TOJ tasks. The relation between the PSS and sensitivity across the two tasks was poor, as neither of these parameters was significantly correlated across the two tasks. Moreover, the PSS in both SJ and TOJ were significantly tactile-leading, indicating that the tactile stimulus had to precede the visual stimulus for simultaneity to be perceived.

Nonsignificant correlations among the PSS and sensitivity measures between SJ and TOJ are consistent with the similar lack of associations that had been shown in the audiovisual modalities (e.g. van Eijk et al., 2008; Love et al., 2013) and indicate that the two tasks may involve distinct processing mechanisms. According to the model used to fit the present data, the visual processing speed showed a significant main effect of task when the data from SJ and TOJ were fit separately, supporting the claim that some additional mechanisms may be involved in completing the TOJ task. This finding comes in contrast with the analyses of García-Pérez & Alcalá-Quintana (2015), which concluded that SJ and TOJ operate under common sensory processes since differences between the two tasks can be accounted for solely by decisional and response factors. Although this may be true, fitting the present data separately uncovered that differences in visual processing may in fact be an additional factor that explains why the SJ and TOJ tasks differ, and is consistent with the increased visual activation for audiovisual TOJs relative to SJs observed in Binder (2015).

Our analyses for the resolution (sensitivity) and response bias parameters were in agreement with García-Pérez & Alcalá-Quintana (2015). Observers' resolution values were significantly lower in TOJ relative to SJ (i.e. they were able to resolve smaller SOAs in TOJ), which may reflect an increased amount of effort exerted by our observers in order to arrive at the correct response, as a result of higher processing demands of the TOJ task. The TOJ task may therefore be more useful when the research goal is to estimate observers' resolution limit (García-Pérez & Alcalá-Quintana, 2012). A longstanding issue in the literature, for which there is currently no general consensus, is whether or not the perception of successiveness is sufficient for the perception of temporal order (Hirsh & Sherrick, 1961; Allan, 1975; Jaśkowski, 1991). One could argue that since the TOJ task exhibited smaller resolution values compared to the SJ task, perceiving successiveness must be sufficient for perceiving temporal order as the opposite would be paired with larger resolution values in TOJ (e.g. van Eijk et al., 2008[5]); this would support the claim that SJ and TOJ involve similar perceptual mechanisms. However, because observers may have exerted less effort while making SJs, it is possible that inaccurate resolution values were obtained from the SJ task, and a conclusion cannot be made while the amount of effort remains a confounding variable (note also that an increased amount of effort due to *perceived* task demands in TOJ would not necessarily reflect the involvement of separate or additional perceptual mechanisms). It will be a challenge for future research to attempt to equalize the observers' amount of effort in

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[5] van Eijk et al. (2008) made this argument with the finding that the simultaneity boundaries for the SJ3 task were within those of the present SJ task. However, García-Pérez and Alcalá-Quintana (2012) showed that the difference in resolution between the data from these two tasks were not significant.

these tasks. Analyses also revealed a significant response bias effect in the TOJ task, where observers were more likely to respond "visual-first" when they were unable to perceive the temporal order. This bias effectively shifts the PSS towards tactile-leading, rendering the TOJ task an inaccurate method of estimating the PSS (see also Schneider and Bavalier, 2003, where differences in PSS between SJ and TOJ were attributed to response biases).

The finding that the PSS was tactile-leading was particularly surprising as the visual stimulus should have required a greater amount of time to be transduced compared to the tactile stimulus (Vroomen & Keetels, 2010). The majority of previous work summarized in Table 1 supports this view: the PSS were vision-leading, though large variations in individual PSS values have been reported (e.g. Poliakoff et al., 2006). Although response bias in the TOJ task is able to account for a tactile-leading PSS, the same effect does not exist in the SJ task and hence cannot explain its similar tactile-leading PSS. Historically, however, there has been heavy debate in the literature regarding the prior entry hypothesis, which states that an attended stimulus is processed more quickly compared to an unattended stimulus (Titchener, 1908; see Spence & Parise, 2010 for a review). For example, Spence et al. (2001) provides some important evidence for prior entry in the visuotactile pairing of modalities. While attending to vision, the visual stimulus had to lead the tactile stimulus by much smaller intervals for simultaneity to be perceived, compared to when attention was directed towards touch; visual information was therefore processed faster when it was attended to. In the present experiment, the distance between the tactile machine and the computer screen may have been great enough such that participants were unable to attend to both modalities at the same time. If our observers voluntarily attended to vision due to its poor attention grabbing nature (i.e. tactile stimuli are felt without the need of prior attention; cf. Posner et al., 1976), it would suggest that tactile information may have required more time to be processed and therefore had to lead in order for simultaneity to be perceived.

Experiment 2

Based on the findings from Experiment 1, we were motivated to conduct Experiment 2 in an effort to determine whether manipulating the spatial distance between the visual and tactile stimulus would affect observers' ability to attend to these stimuli, and therefore the location of the PSS. In Experiment 1, the visual stimulus was presented on an LCD monitor positioned in front of the observer while the tap machine was located directly below, but in peripheral vision. In the present experiment we positioned the tactile stimulus either immediately beside the visual stimulus or at some distance (as in Experiment 1). In addition, we sought to verify that the PSS and sensitivity among SJ and TOJ were indeed uncorrelated.

Method

Participants

Eighteen participants (9 males, 9 females; mean age = 19.2 years, range = 17 to 31 years) were tested in both the simultaneity (SJ) and temporal order judgment (TOJ) tasks of the experiment under both the far and near conditions. Two additional participants (1 male, 1 female; both 18 years of age) did not return for the second session and only completed the far or near condition; their data were used in the separate analyses of far and near but not in the joint analyses between these conditions. Three additional participants were tested but excluded from all analyses because they performed as outliers (see inclusion criteria in Results). One additional participant was excluded for the same reason, but only in the near condition of TOJ (performance was fine in the other conditions). All other details were the same as Experiment 1.

Apparatus and Stimuli

Participants were seated in a black-painted, dimly-lit room with their head on a chin rest place on a 81 cm high by 1.9 m wide table. The stimuli used differed from those in Experiment 1. The visual stimulus was a yellow light presented from a LED located 50 cm directly in front of the chin rest, which was held by a hollow cardboard box 14.3 cm high such that the LED was pointed directly at the participants; the duration of each presentation was 16.7 ms. The tactile stimulus was presented via a wooden cube (8 cm long by 3.5 cm wide by 5.1 cm high), in which an Oticon-A (100 ohms) bone-conducting vibrator was mounted beneath a circular aperture (2 cm in diameter) at the center of the cube; a green LED was also mounted on the top of the cube. Participants held this cube with their right hand, and with their thumb on top of the button. The duration of each vibration was also 16.7 ms. Participants made their responses via two foot pedals placed on the ground underneath the table, at the toes and heel of their right foot. To account for the height of the foot pedals, participants also placed their left food on a wooden plank 4.5 cm high. White noise was played continuously, as in Experiment 1. Presentation of the stimuli was controlled by Matlab (MathWorks Inc., Natick, MA).

Design

The SOAs used were the same as in Experiment 1. Each participant completed both the SJ and TOJ tasks under the "far" and "near" conditions over two separate sessions of one hour each. In the far condition, participants held the wooden cube 5 cm directly in front of the chin rest. In the near condition, they held the cube at the right side of cardboard containing the yellow LED. Nine participants were randomly assigned to complete the "far" condition in the first session, while the remaining nine participants first completed the "near" condition. In addition, ten participants first completed SJ in the "far" condition, while eleven first completed SJ in the "near" condition. All other details were the same as Experiment 1.

Procedure

Participants were instructed to press down on the foot pedals when not responding: a trial did not begin until both pedals were pressed down. For SJ, participants raised their toe from the foot pedal to indicate that the visual and tactile stimuli were presented at the same time, or their heel to indicate that the two stimuli were presented at different times. For TOJ, participants raised their toe to indicate that the visual stimulus was presented first, or their heel to indicate that the tactile stimulus was presented first. Participants were given up to five seconds to respond; if no response was made during this time, the yellow LED and the wooden cube would begin to flash and vibrate continuously at the rate of 5 presentations per second. The experiment continued once the participant raised their right foot and stepped back down on the foot pedals; the no-response trial was repeated at the end of the block.

In both sessions, three separate practice blocks were completed prior to the start of each task as in Experiment 1. During the main SJ and TOJ tasks, both the yellow and green LEDs would lit up to signal the end of each block. Participants were instructed to press the spacebar on a keyboard placed near the right edge of the table once they were ready to continue to the next block.

Results

The same inclusion criteria as Experiment 1 were used for data from the current experiment. However, although two participants did not meet all of the criteria, they were included in our analyses because they only made one additional error outside of the allowed number of errors, which we believe could be simply due to response errors. Eighteen participants remained in the final analyses (Seventeen for analyses involving the near condition of TOJ), and two additional participants were included in the separate analyses of the far and near conditions[6].

The overall mean proportions for SJ and TOJ in the far and near conditions are collectively shown in Figure 3 to illustrate observable difference between the two tasks. The data were submitted to three-way analyses of variance (ANOVA) with between-subject factors of condition order (far vs. near first) and sex and a within-subject factor of SOA; no significant main effects of condition order nor sex were found.

Individual data were fitted with the same R routines as in Experiment 1, from which PSS and sensitivity values were obtained. In both the far and near conditions, the mean PSS for SJ and TOJ were tactile-leading; however, one-tailed *t* tests showed that these were significantly less than zero only in the two near conditions. Repeated measures ANOVAs revealed no significant PSS difference between SJ and TOJ in the far condition ($F(1, 18) = .89$, $p = .36$), while in the near condition, the PSS was marginally more tactile-leading in TOJ ($F(1, 17) = 4.12$, $p = .06$). In addition, the PSS in SJ was

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[6] On rare occasions, an error caused the computer to record both possible responses for a trial (e.g. both "same" and "different" responses for an SJ trial). These trials accounted for approximately 0.1% of all trials and were removed from further analyses.

marginally more tactile-leading in the near condition (*F*(1, 17) = 3.83, *p* = .07) while the difference in TOJ PSS was not significant (*F*(1, 16) = .74, *p* = .40).

Repeated measures ANOVAs on the sensitivity measure between SJ and TOJ were not significantly different in the far condition (*F*(1, 18) = .72, *p* = .41), but participants showed higher sensitivity in TOJ in the near condition (*F*(1, 17) = 7.57, *p* = .01). Moreover, the sensitivity difference between far and near was not significant in SJ (*F*(1, 17) = .53, *p* = .48) whereas in TOJ, participants showed higher sensitivity in the near condition (*F*(1, 16) = 6.55, *p* = .02).

Additional analyses for the sensory and response parameters were carried out as in Experiment 1, and here we highlight the effects that were revealed to be significant. In the near condition, the visual processing speed was faster in SJ compared to TOJ (λ_V, *F*(1, 17) = 4.51, *p* = .05). The difference in processing delay (τ, *F*(1, 17) = 9.66, *p* < .01) between SJ and TOJ was also significant in the near condition: the mean τ in "near" SJ was significantly greater than zero (*t*(18) = 2.67, *p* < .01), suggesting that the visual stimulus arrived first at the central mechanism when both stimuli were presented simultaneously, whereas the mean τ were marginally less than zero in both TOJ conditions (far: *t*(18) = -1.65, *p* = .06; near: *t*(17) = -1.51, *p* = .07), suggesting that the tactile stimulus first arrived at the central mechanism. Once again, using the same method of calculation as in Experiment 1, we found that participants appeared to be more error-prone in TOJ compared to SJ. Finally, two-tailed *t* tests showed that the response bias (ξ) in TOJ was significantly greater than chance level in both the far (*t*(18) = 2.37, *p* = .01) and near conditions (*t*(17) = 3.34, *p* < .01), indicating that participants were biased towards responding "visual-first". The mean and standard error of all the parameters from the fitting procedure are shown in Table 3.

The data were also submitted to several correlation calculations, as in Experiment 1, as well as additional within-task correlations in order to examine the reliability of the two tasks. The correlations between SJ and TOJ are shown in Figure 4a, and the within-task correlations are shown in Figure 4b. The PSS among SJ and TOJ appear to be unrelated in both the far (r = -.14, p = .56) and near conditions (r = .28, p = .25). Similarly, the sensitivity among SJ and TOJ were also unrelated in both the far (r = .22, p = .37) and near conditions (r = .08, p = .76). The SJ PSS exhibited a strong relation between far and near (r = .60, p < .01) but for TOJ PSS this relation was weak (r = .36, p = .15). For sensitivity, the relation between the far and near conditions was weak in both SJ (r = .39, p = .11) and TOJ ($r \approx 0$, p = .99). These results were verified with the same bootstrapping procedure in Experiment 1; the mean of the distribution in each case closely matched the correlation coefficients stated above, and for all nonsignificant correlations, r = 0 (i.e. no correlation) was within the 95% confidence interval of the frequency distribution.

Figure 3: mean proportions of "same" and "visual-first" responses in SJ and TOJ, in both the far and near conditions, across all participants. Error bars represent standard error of the mean at each SOA.

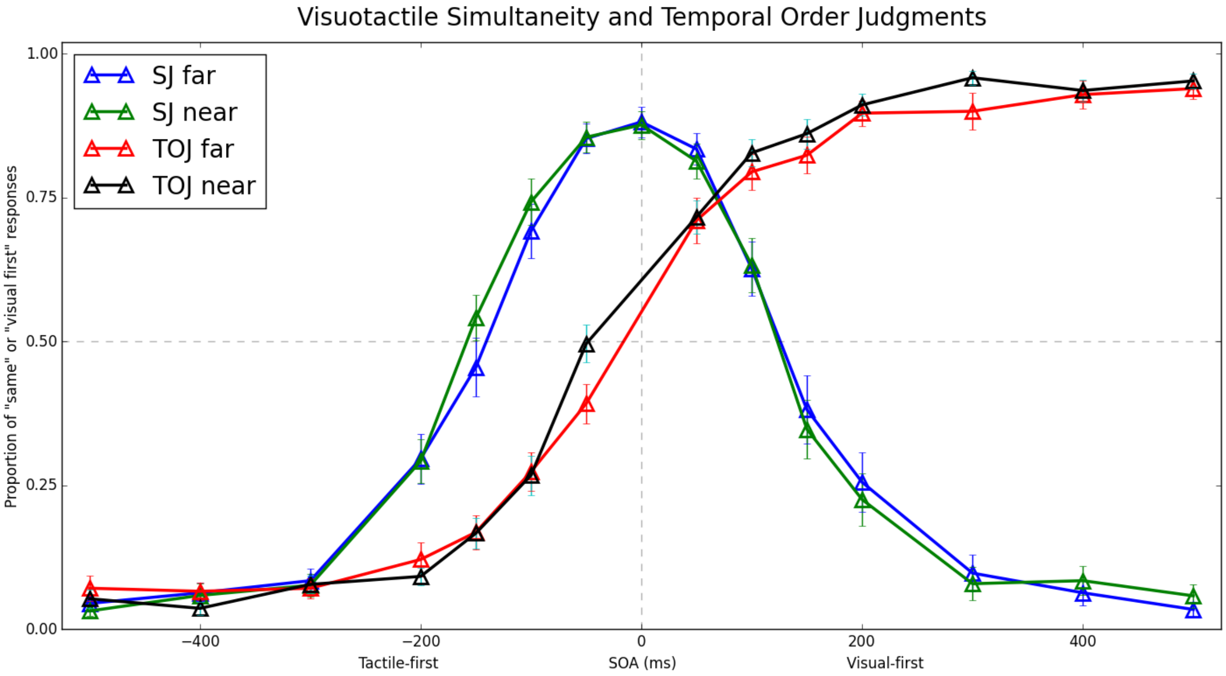

Figure 4a: correlations of the PSS and sensitivity between SJ and TOJ in the far and near conditions.

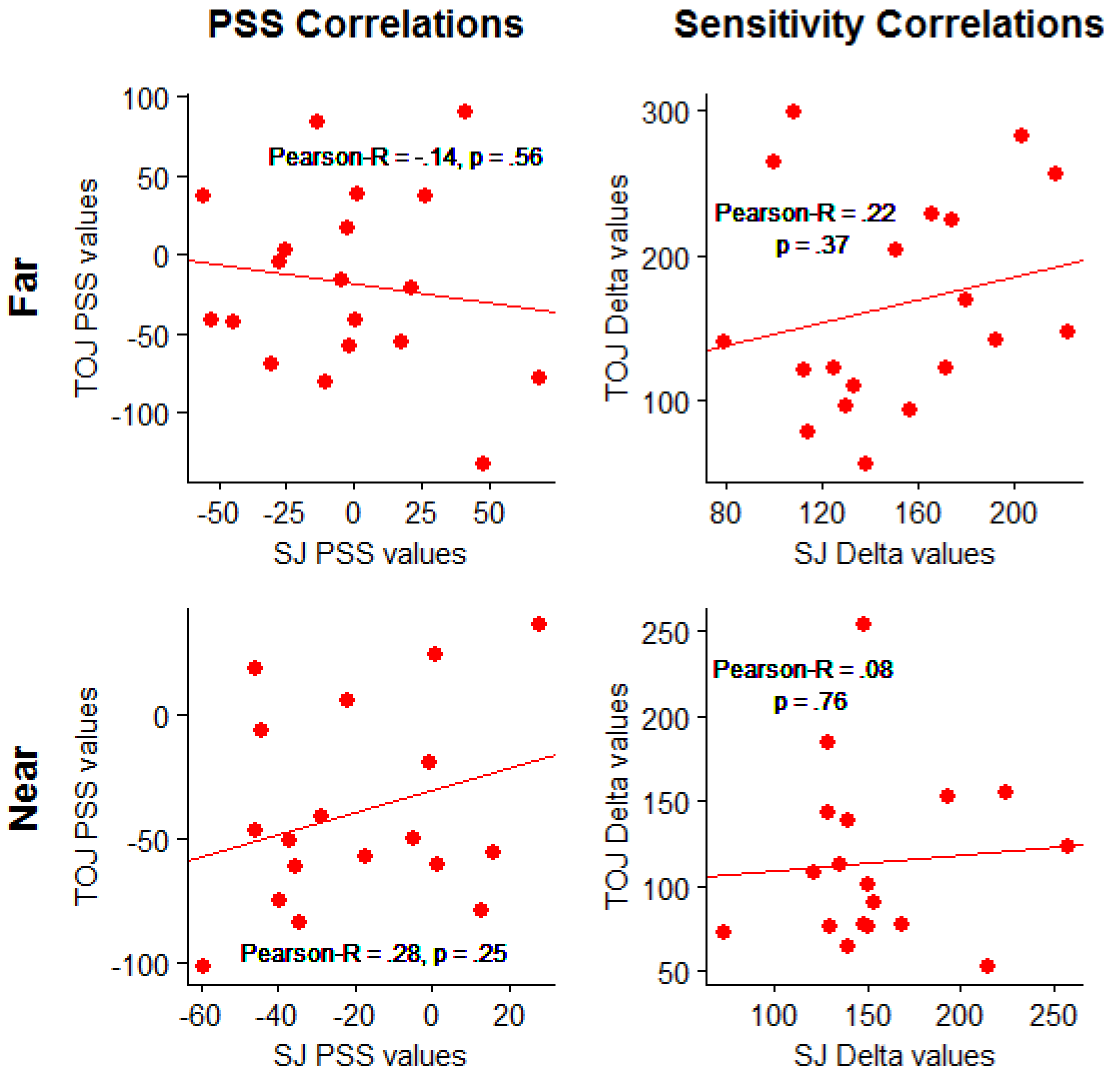

Figure 4b: correlations of the PSS and sensitivity between the far and near conditions within each task.

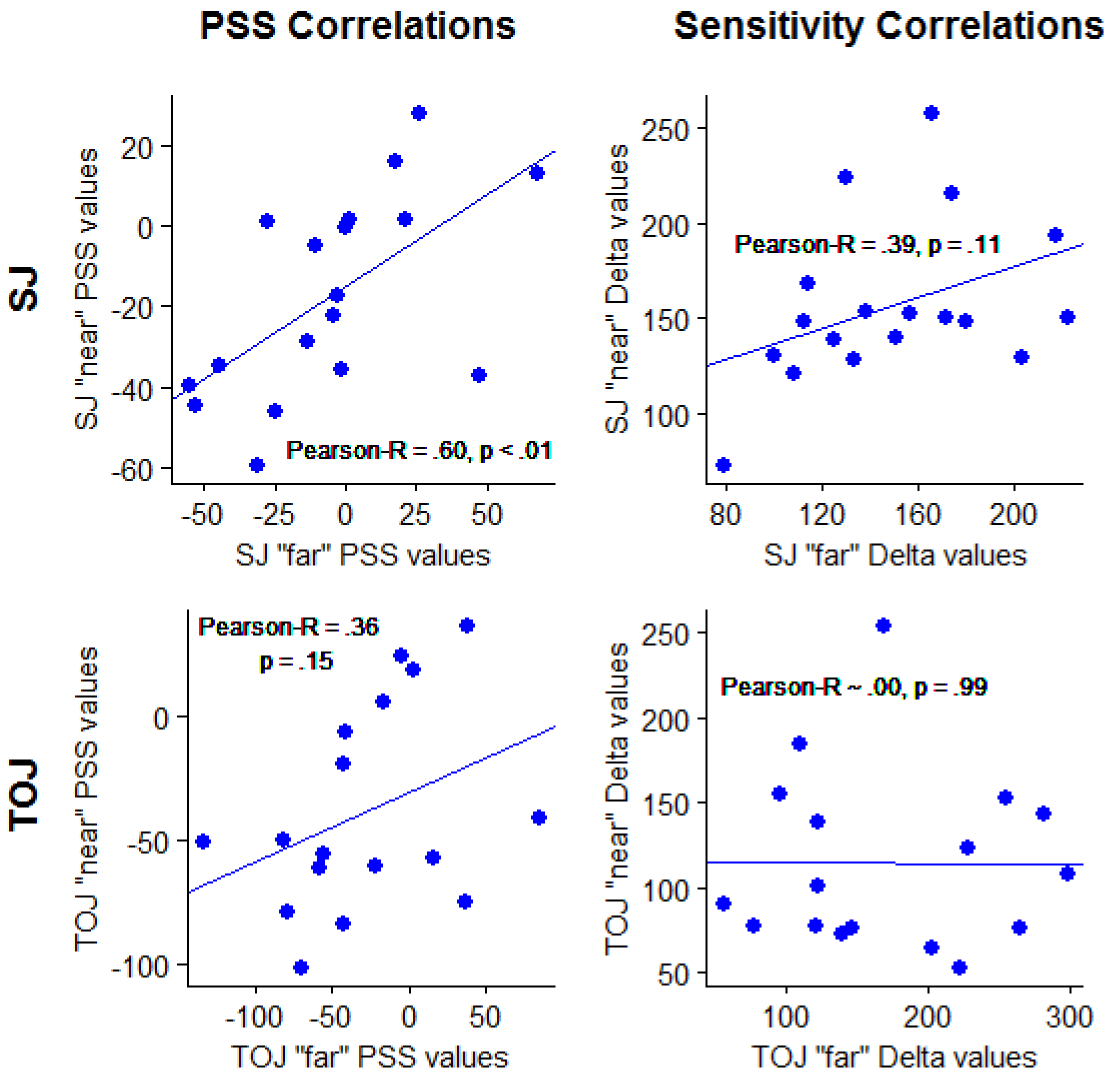

Table 3: mean and standard error of the estimated parameters from Experiment 2. Negative PSS values indicate that they were located on the tactile-leading side.

	Far SJ		Far TOJ		Near SJ		Near TOJ	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
PSS	-2.41	7.72	-17.90	13.42	-18.71	5.75	-39.29	9.39
λ_V	.070	.027	.141	.033	.105	.029	.111	.033
λ_T	.074	.027	.105	.027	.054	.023	.156	.033
τ	-1.79	13.97	-51.71	31.38	36.99	13.85	-36.84	24.34
δ	151.30	9.38	166.12	16.93	155.82	9.60	114.70	11.91
ε_{VF}	.048	.019	.068	.020	.052	.016	.044	.013
ε_{TF}	.049	.013	.102	.052	.031	.010	.049	.012
ε_S	.077	.027	-	-	.078	.026	-	-
ξ	-	-	.651	.064	-	-	.664	.049

Discussion

The main goal of this experiment was to test whether the tactile-leading PSS values shown in Experiment 1 were caused by prior entry effects in the visual modality. Although the difference in PSS approached significance in SJ, we generally did not observe a great amount of change in the range of PSS values between the far and near conditions, and the mean PSS remained tactile-leading in all conditions. Moreover, we replicated the poor relation between SJ and TOJ in terms of the PSS and sensitivity parameters, though we now suspect that the reliability of the two tasks is a significant contributing factor.

The lack of change in the PSS between the far and near conditions was confirmed by nonsignificant differences for the sensory parameters (λ and τ) between the two conditions. This finding indicates that changing the spatial location of the tactile stimulus to encourage a visual prior entry effect did not actually influence the location of the PSS. It may also be a reflection of the fact that observers are never able to completely divide their attention between sensory modalities, and even though we reduced the spatial distance between the visual and tactile stimulus, the nature of their saliency (i.e. the amount of attention that is elicited) did not change. However, as we did not explicitly instruct observers to attend to any particular feature in the experiment, we cannot conclude for certain the role of prior entry in our data. At this stage, we noticed a possible alternative explanation—uncertainty—that might instead have affected the location of the PSS. By comparing the studies listed in Table 1, it is apparent that those which had produced a vision-leading PSS when measuring visuotactile integration had also presented the stimuli from both the left and right sides of space with equal likelihood, and observers were not explicitly instructed to attend to specific locations (e.g. Spence et al., 2001; Spence et al., 2003; Poliakoff et al., 2006; Finkelshtein, 2015), whereas similar to the current experiments, Noel et al. (2015) and Van de Burg et al. (2015) presented the visual and tactile stimuli from only one location and the reported PSS values are clearly tactile-leading. Experiments 3 and 4 in Spence et al. (2001) provides further evidence for the spatial uncertainty hypothesis: when subjects were instructed to attend to either the left or right side of space, the visual and tactile stimulus each had a 75% chance of occurring on that side for a given trial (they did not both appear on the opposite side); therefore, subjects were more certain than chance that a stimulus will appear on the attended side. When the right side of space was attended to, the PSS shifted towards tactile-leading when both stimuli occurred on that side, revealing a possible effect for when there is greater certainty of stimulus location. None of these studies had explicitly mentioned the effect of stimulus location uncertainty. In our next experiment, we explicitly manipulated spatial uncertainty.

Our analyses in Experiment 2 showed, again, that there were no significant relation among the PSS and sensitivity in the SJ and TOJ tasks. Here, we highlight one result from the current experiment that we had not found in Experiment 1: while the delay parameter τ was positive in one SJ condition (and did not differ significantly from zero in the other), the same parameter was negative in both TOJ conditions, suggesting that the order in which the stimuli arrived at the central mechanism were different in the two tasks. At face value, this can be interpreted as another possible sensory processing difference between SJ and TOJ; however, by comparing the remaining results from Experiment 2, we suspect that task reliability may be a potential confound in our findings as well as similar findings in the literature. To begin with, we only revealed differences in the visual processing speed and the delay parameters in the near condition, but not in the far condition (i.e. the condition most similar to Experiment 1, where we revealed a difference in the visual processing speed). In addition, we showed a significantly higher sensitivity in TOJ relative to SJ only in the near condition; interestingly, the sensitivity in TOJ across the two conditions also displayed a significant difference (when the same observers were tested), and is likely to have affected the sensitivity difference between SJ and TOJ. Within-task correlations of the PSS and sensitivity were relatively higher in SJ than TOJ, indicating that these two parameters are perhaps more reliably obtained in SJ, although only the PSS in this task was significantly correlated across conditions. Taken together with the analyses of García-Pérez & Alcalá-Quintana (2012) and Love et al. (2013), there is reason to question the reliabilty of the SJ and TOJ tasks, which is crucial especially if it plays an important role in how the two tasks correspond with each other (rather than differences that may be present in sensory processing).

Experiment 3

In our final experiment, the certainty of stimulus location was manipulated separately for the visual and tactile stimuli in order to test how each manipulation independently affects the PSS. We also evaluated the reliability of the SJ and TOJ tasks by examing the correlations withing each task. The critical assumption in all previous work examining the relation between SJ and TOJ is that both measures are reliable. This assumption was tested here.

Method

Participants

In the tactile uncertainty condition, eighteen participants (5 males, 13 females, mean age = 19 years, age range = 18 to 22 years) were tested in the SJ tasks, and seventeen participants (5 males, 12 females, mean age = 19 years, age range = 18 to 22 years) were tested in the TOJ tasks. Four additional participants were tested in the SJ tasks but excluded from the final analyses because they performed as outliers (see inclusion criteria in Results). Similarly, five additional participants were tested but excluded from the analyses of the TOJ tasks. In the vision uncertainty condition, nineteen participants (4 males, 15 females, mean age = 19 years, age range = 18 to 32 years) were tested in the SJ tasks, and twenty participants (5 males, 15 females, mean age = 19 years, age range = 18 to 32 years) were tested in the TOJ tasks. Three additional participants were tested in the SJ tasks but excluded from the final analyses because they performed as outliers. Similarly, two additional participants were tested but excluded from the analyses of the TOJ tasks. All other details remained the same.

Apparatus and Stimuli

The equipment used was the same as Experiment 2, with the following changes to the presentation of the stimuli. In the tactile uncertainty condition, the tactile stimulus was presented from one of two identical cubes and the visual stimulus was a presented from a red central LED. In the vision uncertainty condition, the visual stimulus was presented from one of two red LEDs, and the tactile stimulus was presented from one single cube held centrally. In the certain condition, the visual stimulus was a red light presented from a red/green dual LED mounted on top of a cube from which the tactile stimulus was also presented.

Design

The SOAs were the same as in Experiments 1 and 2. Each participant completed both the SJ and TOJ tasks under one of the two uncertainty conditions, as well as the certain condition, over two separate sessions totaling 1.5 hours (1 hour for session one). In the "tactile uncertainty" condition, participants held one wooden cube in each hand positioned 22.5 cm to either side of center; the tactile stimulus was presented randomly from one of these two cubes, and the visual stimulus was presented from a central location. In the "vision uncertainty" condition, the visual stimulus was presented randomly at one of the two LEDs located 22.5 cm at each side of the participant and 50 cm in front, and the tactile stimulus was presented from one cube held centrally. In the "certain" condition, participants held one cube with their right hand at the center of the table, and both the tactile and the visual stimulus were presented from this cube. The order of the conditions and tasks was counterbalanced.

Procedure

In the uncertain conditions, one red and one green LED lit up to signal the end of a block. In the certain condition, this was signalled by the single green LED. Otherwise, the procedure remained the same as Experiment 2.

Results

The inclusion criteria remained the same, with the following exceptions. In the tactile uncertainty condition, one participant did not meet all of the criteria in the SJ task, but was still included in our analyses because they only made one additional error outside of the allowed number of errors, which could be simply due to a response error. One additional participant was excluded from the analyses of TOJ due to overall poor performance, even though they had met all of the criteria. Eighteen participants remained in the analyses of SJ, and seventeen in the analyses of TOJ. In the vision uncertainty condition, two participants in SJ and three in TOJ did not meet all of the criteria, but were still included for the same reason as above. Nineteen participants remained in the analyses of SJ, and twenty in the analyses of TOJ. A total of six participants across both conditions who did not return for their second session were excluded from all analyses. Finally, in the comparisons of sensitivity between SJ and TOJ, those who were already excluded from one task were also excluded from the other task.

Figure 5a shows the overall mean proportions for SJ and TOJ in the tactile uncertainty condition as well as its corresponding certain condition (i.e. the dataset of participants who were also assigned to tactile uncertainty). Figure 5b shows these proportions for the vision uncertainty condition and its corresponding certain condition.

The data were submitted to two-way analyses of variance (ANOVA) with a between-subject factor of condition order (uncertain vs. certain first) and a within-subject factor of SOA; no significant effects of condition order were found.

The fitting procedure remained the same as the previous two experiments. The overall PSS was tactile-leading in all tasks within each condition. For the tactile uncertainty condition, there was no difference in the PSS between the certain and uncertain conditions ($F(1, 17) = .19$, $p = .67$ for SJ and $F(1, 18) = .47$, $p = .50$ for TOJ), although in TOJ there appears to be a vision-leading shift in the PSS from uncertain to certain. In the vision uncertainty condition, similar analyses revealed nonsignificant PSS differences in SJ ($F(1, 18) = 1.36$, $p = .26$) and TOJ ($F(1, 19) = 1.91$, $p = .18$), although again in TOJ, there appears to be a vision-leading shift in the PSS from uncertain to certain. No significant differences for the processing speed (λ) nor delay (τ) were found in the comparisons between the uncertain and certain conditions. The mean τ was greater than zero in all except one of the "certain" datasets, suggesting that the visual stimulus arrived first at the central mechanism when both stimuli were presented simultaneously; however, these were only significant in SJ for tactile uncertainty ($t(17) = 2.41$, $p = .01$) and vision uncertainty ($t(18) = 2.63$, $p < .01$). Sensitivity was higher in TOJ relative to SJ in the tactile uncertainty ($F(1,17) = 7.55$, $p = .01$) and the vision uncertainty conditions ($F(1,19) = 7.80$, $p = .01$), as well as the certain condition for those who completed vision uncertainty ($F(1,19) = 15.07$, $p < .01$). Analyses of the response bias (ξ) was somewhat less conclusive for the current experiment, with those in the certain condition corresponding to tactile uncertainty ($t(16) = 2.22$, $p = .02$) and the vision uncertainty condition ($t(19) = 1.79$, $p = .04$) being significantly greater than chance level. The mean and standard error of all the parameters from the fitting procedure are shown in Tables 4a and 4b.

To examine the reliability of the SJ and TOJ tasks, we first computed the correlations for the PSS and sensitivity between the uncertain and certain conditions of each task. The results are displayed in Table 5a as well as in Figure 6a. SJ correlations were significant in three of the four comparisons, while in TOJ none were significant; this indicates that the SJ task may be more reliable overall. In order to verify these results, a split-half analysis was carried out where each participant's data (within each condition) was randomly divided in half and correlations for the PSS and sensitivity were computed between the two halves. The results are displayed in Table 5b as well as in Figure 6b. Although the correlations in SJ remained higher overall, comparisons of the PSS yielded more significant correlations in TOJ, indicating that the TOJ task appears to more reliably measure the PSS. Interpretations for these results are outlined in the discussion.

Figure 5a: mean proportions of "same" and "visual-first" responses in SJ and TOJ, in the tactile uncertainty condition with the corresponding certain condition, across all participants. Error bars represent standard error of the mean at each SOA.

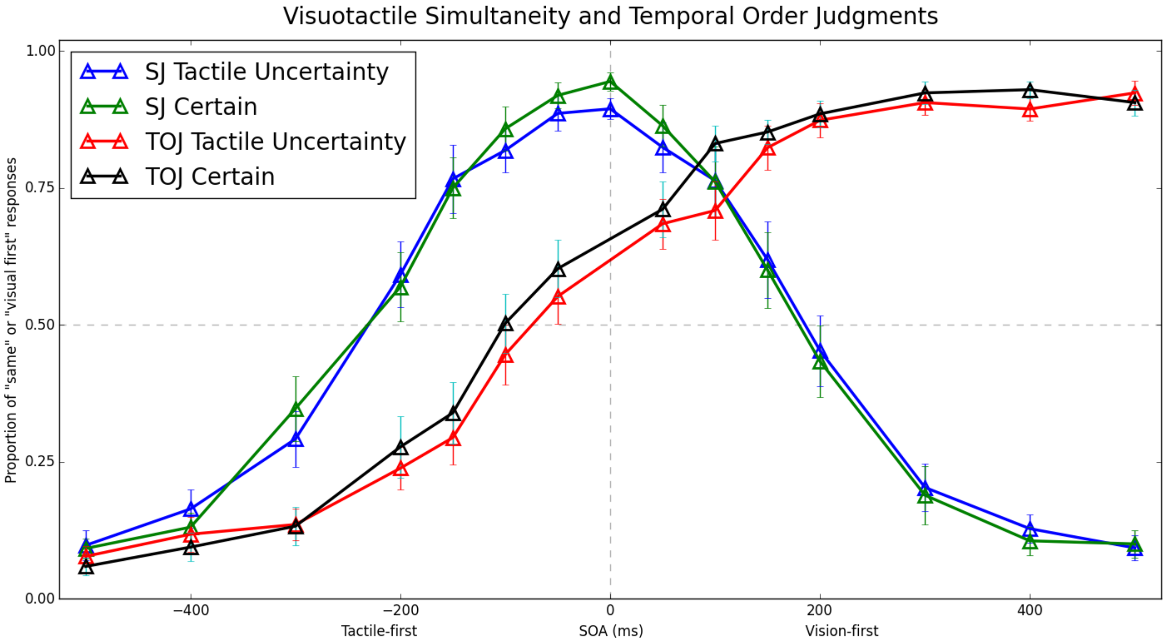

Figure 5b: mean proportions of "same" and "visual-first" responses in SJ and TOJ, in vision uncertainty condition with the corresponding certain condition, across all participants. Error bars represent standard error of the mean at each SOA.

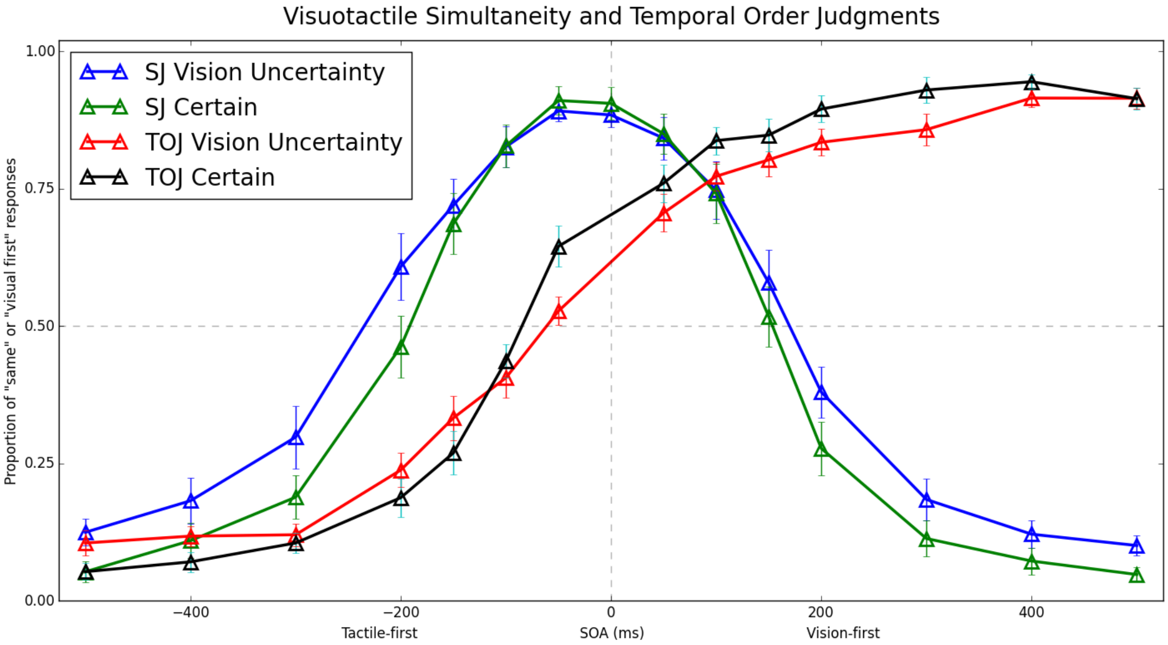

Figure 6a: correlations of the PSS and sensitivity between the uncertain and certain conditions. *TU = tactile uncertainty; VU = vision uncertainty; C = certain.* Refer to Table 5a for specific statistical values.

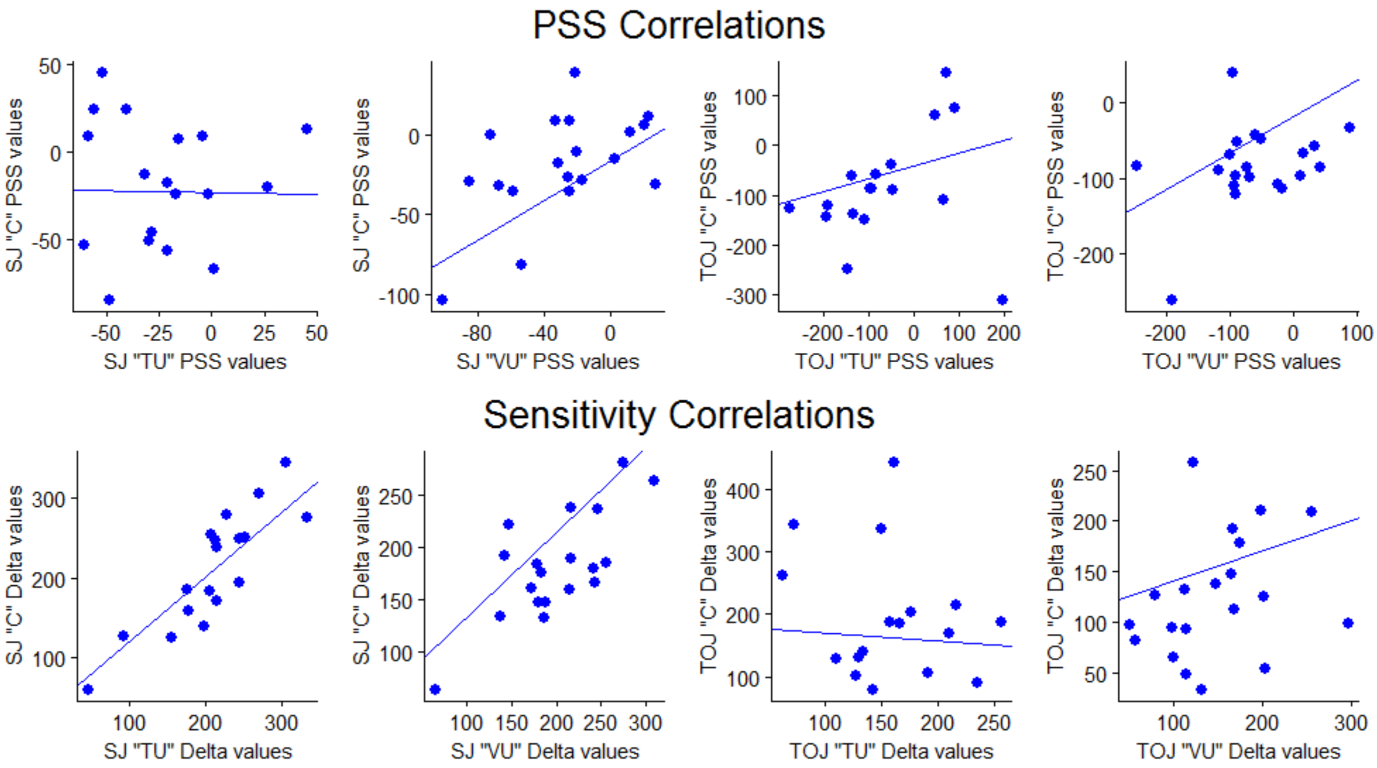

Figure 6b: correlations of the PSS and sensitivity in the split-half analyses of task reliability. In each plot, the data was collapsed across the uncertain and certain conditions (e.g. the "tactile" plots contain data from participants who completed the tactile uncertainty condition, as well as the corresponding certain condition), since the PSS and sensitivity did not significantly differ between these conditions. Refer to Table 5b for specific statistical values.

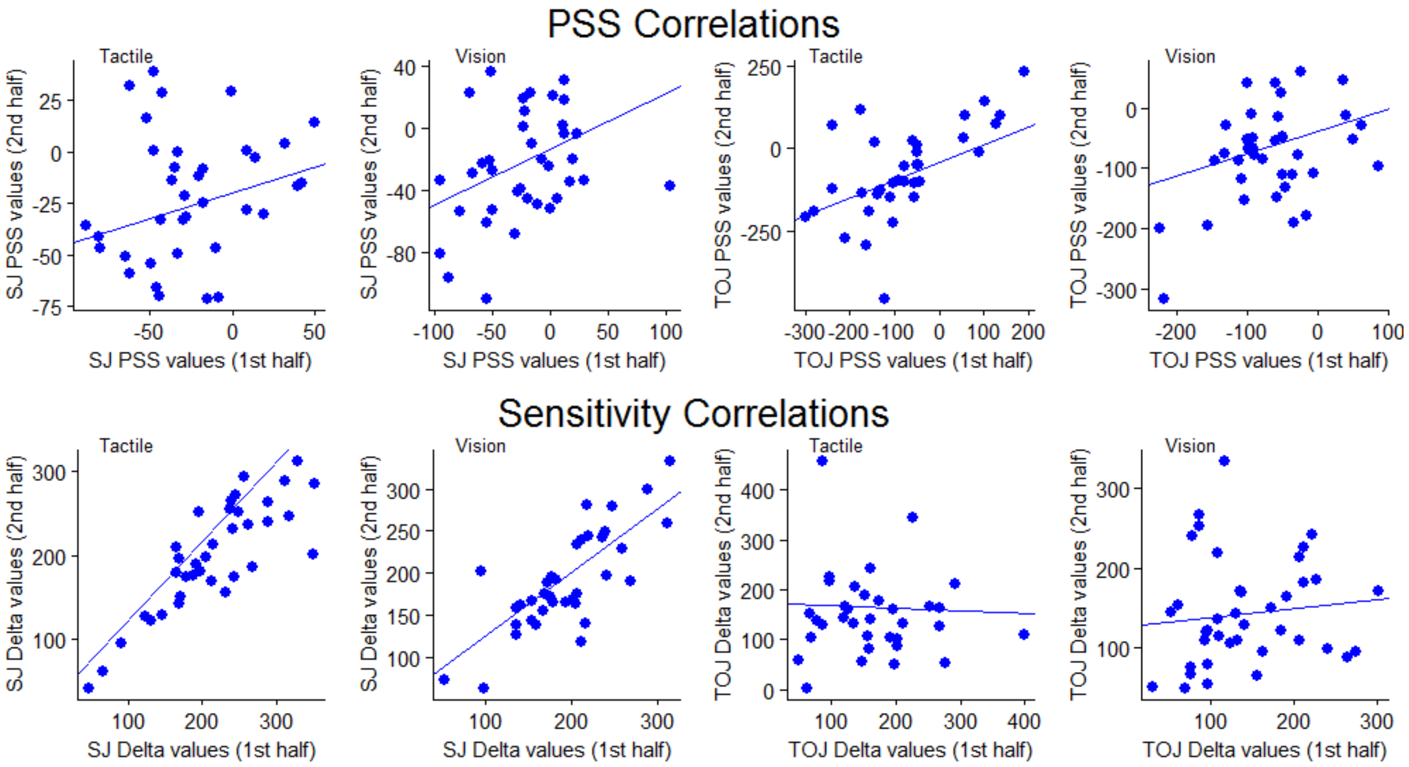

Table 4a: mean and standard error of the estimated parameters from Experiment 3 for tactile uncertainty. Negative PSS values indicate that they were located on the tactile-leading side.

	Uncertain SJ		Certain SJ		Uncertain TOJ		Certain TOJ	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
PSS	-22.93	6.82	-18.19	8.47	-63.78	29.52	-87.72	26.86
λ_V	.113	.031	.067	.027	.116	.033	.181	.034
λ_T	.058	.022	.097	.030	.150	.036	.105	.036
τ	35.19	14.63	-2.17	16.07	36.63	27.69	38.94	35.00
δ	210.06	16.20	210.84	17.27	158.63	12.75	194.63	24.38
ε_{VF}	.087	.024	.082	.020	.078	.020	.246	.089
ε_{TF}	.111	.027	.067	.014	.061	.018	.046	.013
ε_S	.071	.021	.031	.014	-	-	-	-
ξ	-	-	-	-	.543	.060	.647	.066

Table 4b: mean and standard error of the estimated parameters from Experiment 3 for vision uncertainty. Negative PSS values indicate that they were located on the tactile-leading side.

	Uncertain SJ		Certain SJ		Uncertain TOJ		Certain TOJ	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
PSS	-28.80	8.51	-19.80	7.52	-59.91	17.56	-84.40	12.42
λ_V	.067	.024	.071	.027	.168	.030	.115	.029
λ_T	.059	.023	.087	.030	.129	.030	.144	.030
τ	37.78	14.39	13.84	16.19	28.62	27.67	33.67	24.19
δ	200.11	13.00	182.26	11.65	148.52	14.05	125.03	13.40
ε_{VF}	.094	.017	.050	.011	.075	.018	.082	.021
ε_{TF}	.113	.025	.060	.016	.096	.018	.055	.016
ε_S	.056	.014	.050	.021	-	-	-	-
ξ	-	-	-	-	.589	.049	.547	.052

Table 5a: within-task correlations of the PSS and sensitivity. *TU = tactile uncertainty; VU = vision uncertainty; C = certain; ** indicates significance.*

Comparison	PSS	Sensitivity
SJ TU/C	r = -.02; p = .93	r = .86; p < .01**
SJ VU/C	r = .54; p = .02**	r = .73; p < .01**
TOJ TU/C	r = .23; p = .37	r = -.24; p = .36
TOJ VU/C	r = .34; p = .14	r = .28; p = .23

Table 5b: split-half correlations of the PSS and sensitivity. *TU = tactile uncertainty; VU = vision uncertainty; C = certain; ** indicates significance; * indicates marginal significance.*

Comparison	PSS	Sensitivity
SJ TU	$r = .12$; $p = .65$	$r = .82$; $p < .01$**
SJ VU	$r = .41$; $p = .08$*	$r = .73$; $p < .01$**
SJ C (TU subjects)	$r = .32$; $p = .19$	$r = .86$; $p < .01$**
SJ C (VU subjects)	$r = .21$; $p = .39$	$r = .84$; $p < .01$**
TOJ TU	$r = .62$; $p < .01$**	$r = .08$; $p = .77$
TOJ VU	$r = .39$; $p = .08$*	$r = -.13$; $p = .58$
TOJ C (TU subjects)	$r = .69$; $p < .01$**	$r = -.28$; $p = .28$
TOJ C (VU subjects)	$r = .44$; $p = .05$**	$r = .26$; $p = .28$

Discussion

This experiment had two major goals. First, we tested whether or not being uncertain of the location of the stimuli would shift the PSS towards vision-leading. Our analyses produced nonsignificant results in all cases, although there is an apparent vision-leading shift in the PSS in the TOJ tasks. Second, the reliability analyses suggest that overall, the SJ task may be more reliable compared to TOJ; however, the TOJ task seems to yield more reliable estimates of the PSS. The potential problems for these interpretations of task reliability are discussed below.

Here, we outline two reasons for why the PSS might shift towards vision-leading when stimulus location is uncertain. Previous research has showed that a stimulus which appears on the same side of a space as a "cue" is processed faster than one that appears on the opposite side of space (Driver & Spence, 1998), as well as that slower processing occurs not only for sensory modalities that are unattended, but also when attention needs to be divided between locations compared to always focusing on one location at which the stimulus is presented (i.e. attending to more than one location shifts the PSS; Spence et al., 2001). When the location of the visual stimulus was uncertain, observers would have needed to divide their attention between two locations and required a longer time to process the visual stimulus relative to when its location was certain, and hence the observation of a more vision-leading PSS. Interestingly, we also observed a more vision-leading PSS when the location of the tactile stimulus was uncertain. This suggests that the uncertain modality may actually be processed faster because observers attend more to that modality (i.e. the tactile stimulus would be processed faster when its location was uncertain). We therefore offer another explanation for the vision-leading PSS shift under vision uncertainty, which is that the visual and tactile stimulus were presented in the periphery when they come from one of two locations. Presenting the tactile stimulus in the periphery should not have resulted in an increased processing time; however, various studies have shown that visual processing is slower in the periphery relative to central (e.g. Tynan & Sekuler, 1982; Loke & Song, 1991) and that peripheral processing requires additional cortical structures (Prado et al., 2005). Given that our data only showed a small change in the PSS in the TOJ tasks and none in the SJ tasks, further research is necessary to determine the circumstances under which the PSS may shift when the stimulus location is uncertain.

The highlight of this experiment was identifying how the reliability of the SJ and TOJ tasks might affect our previous findings as well as those in the literature. Comparisons of the PSS and sensitivity between the uncertain and certain conditions revealed significant correlations in the SJ task, but none in the TOJ task. These findings indicate that the SJ task may be overall more reliable than TOJ, and inconsistent measurements from the TOJ task may in part be responsible for the nonsignificant correlations between SJ and TOJ reported here and elsewhere. To be clear, reliability does not provide an indication of accuracy for the two tasks. High correlations for the PSS in the SJ task indicate that the synchrony boundaries changed consistently among participants between datasets, but do not provide information about how accurately the SJ task estimates the actual PSS. In addition, we argued in Experiment 1 that the TOJ task may produce a more accurate estimate of the sensitivity, and in support of this finding, the present experiment also showed that estimates of the sensitivity were smaller in TOJ than SJ; however, sensitivity in SJ showed stronger between-condition correlations compared to TOJ. We suspect that in SJ, observers had set their own synchrony thresholds and that their method of setting this threshold stayed similar between the uncertain and certain conditions, whereas in TOJ, a great amount of effort was needed for observers to push their resolution limit in order to arrive at the correct response, and that they were unable to sustain this effort between the two conditions. In other words, observers were able to "select" their simultaneity thresholds in SJ and this property of the SJ task resulted in stronger correlations of the sensitivity, rather than truly accurate estimates of the sensitivity. To support these interpretations, we computed correlations for the two synchrony boundaries of SJ between the uncertain and certain conditions, all of which were highly significant and indicate that the synchrony boundaries changed consistently across conditions within an individual.

The reliability measurements were further examined with split-half analyses, which again produced highly significant correlations for the sensitivity in SJ, and, in contrast with the previous analysis, a greater number of significant correlations for the PSS in TOJ. These results are in agreement with those in Love et al. (2013) for audiovisual SJ and TOJ. We previously argued that response bias in TOJ tasks was a critical factor for determining the location of the PSS, and here we suspected that these strong correlations for the PSS were caused by consistent response biases, rather than reflecting accurate estimates of the PSS. However, we did not find significant correlations of the response biases in the split-half data. This seems to indicate that another factor is influencing the strong correlations of the PSS in the TOJ tasks. Based on the current data, we are unsure what these other influences may be and further research will be required to determine them, if they do exist. The finding that the SJ task produced higher correlations overall of the PSS, however, supports it as a more ideal way of estimating the PSS relative to TOJ, as the synchrony boundaries in SJ seem to remain consistent. Sensitivity correlations yielded similar results as the first analysis procedure and our previous argument regarding the accuracy of the estimated sensitivity in SJ and TOJ remains applicable.

General Discussion

The study compared precision and accuracy measurements from simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks to examine the hypothesis that these two tasks tap similar cognitive processes. Participants made visuotactile SJs and TOJs under different experimental conditions and we computed between-task correlations in Experiments 1 and 2, and within-task correlations in Experiments 2 and 3. Consistent with recent findings in the literature, we found no significant correlations among the estimated PSS and sensitivity between the visuotactile SJ and TOJ tasks. However, the conclusion that these tasks do not measure the same thing was brought into question by poor reliability for both tasks. Although the SJ task appears to provide more reliable measurements of the PSS and the TOJ task a more reliable measure of sensitivity, neither were highly reliable. These findings have critical implications for future research in multisensory integration, as choice of task may significantly impact experimental results and, in contrast to what has generally been assumed throughout the literature, are not interchangeable.

The visuotactile SJ and TOJ tasks appear to differ in sensory processing

The present study revealed that observers' PSS and sensitivity, as measured by the SJ and TOJ tasks, were not significantly correlated for the visuotactile pairing of modalities. Based on the model which we used to fit the current data (García-Pérez & Alcalá-Quintana, 2012), we determined that these task differences appear to be the result of sensory processing in addition to response factors. In particular, under certain conditions, the visual processing speed and processing delay parameters were significantly different between SJ and TOJ. It appears that using different tasks leads to differential processing speeds in the visual modality, possibly due to the way that the signals are analyzed in the brain (Binder, 2015); however, further evidence is necessary as not all of our experimental conditions showed such a difference (i.e. no delay difference in Experiment 1, no difference in visual processing speed nor delay in the "far" condition of Experiment 2). Task reliability may also have a role in finding these sensory differences, as we will discuss below.

The TOJ task as a more accurate measure of sensitivity

The present experiments revealed that the SJ and TOJ tasks differed in a number of ways that influenced how observers responded in each task. To begin with, we found that in most of our experimental conditions, observers' estimated sensitivity values were significantly smaller in TOJ compared to SJ, indicating that they were able to distinguish smaller SOAs in the TOJ task. However, rather than reflecting similar perceptual mechanisms for the two tasks (cf. Hirsh & Sherrick, 1961; Allan, 1975; Jaśkowski, 1991; van Eijk et al., 2008), it is possible that observers were responding to increased task demands in the TOJ task (García-Pérez & Alcalá-Quintana, 2012; Love et al., 2013). Subjectively, participants find the TOJ tasks to be more difficult (Love et al., 2013), and in that experiment exclusion rates for TOJ were somewhat higher than those in SJ. Observers in the present experiments tended to make more errors in the TOJ tasks compared to the SJ tasks. Although further research is needed to assess the usefulness of these measures, we believe that attentive observers would have responded to the perceived increase in task difficulty with more concentration when making TOJs, in order to arrive at the correct answer. In line with this argument, García-Pérez & Alcalá-Quintana (2012) reasoned that the smaller sensitivity (resolution) values indicate that observers were aiming to achieve their best possible performance when they experienced difficulty of making forced-choice responses in the TOJ task, and hence it is the best method of measuring their true sensitivity[7].

The task reliability results also support the TOJ task as more capable of accurately estimating sensitivity, even though we showed that sensitivity was more reliably estimated in the SJ tasks. Since the SJ task instructs observers to indicate whether or not two stimuli were presented simultaneously and they have no knowledge of the SOAs that are presented (i.e. the proportion of trials that are simultaneous versus not simultaneous), each observer is free to choose their own synchrony criterion based on what they believe to be the correct setting (Vroomen & Keetels, 2010). The estimated sensitivity would therefore reflect what the observer selects as their synchrony boundary, rather than their true ability for distinguishing small SOAs. The strong reliability of the SJ task in measuring sensitivity appears to be the result of observers simply maintaining their synchrony criterion throughout different experimental conditions. In contrast, the TOJ task forces observers to select the stimulus that was presented first and, in doing so, drives the observer's motivation to respond correctly on each trial. We interpret the lack of reliability for the TOJ tasks in measuring sensitivity as an indication that observers were unable to sustain the amount of effort needed to achieve their highest ability for

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[7] For this reason, García-Pérez & Alcalá-Quintana (2012) argued that even though the SJ3 task (van Eijk et al., 2008) appears to be the best task choice overall, the TOJ task remains the most accurate method for estimating the sensitivity.

distinguishing small SOAs throughout the entire task. In other words, the inconsistent sensitivity values for the same group of observers are the result of the attentional demands of the TOJ task, which, assuming that observers put forth their best effort in determining the correct response, leads to a more accurate measure of the true sensitivity relative to the SJ task.

The SJ task as a more accurate measure of the PSS

In the TOJ task, observers must respond with a guess when they are unsure which of the two modalities was presented first. If their guesses are not entirely neutral in these situations, any decisional biases will be confounded with the observer's perception (Schneider & Bavalier, 2003; Zampini et al., 2005b; García-Pérez & Alcalá-Quintana, 2012). Since the PSS is taken as the SOA where observers are maximally unsure of the temporal order, the presence of any response biases will shift the location of the PSS towards one of the two modalities and away from its true value, resulting in an inaccurate estimate of the PSS. For this reason, the SJ task is more appropriate when the primary goal is to test for changes in the PSS, as it should remain consistent even when observers change their synchrony criterion (Schneider & Bavelier, 2003). In support of these claims, our analyses revealed that observers had a vision-first response bias in most of the TOJ tasks across our three experiments, which would have shifted the true PSS towards tactile-leading.

The reliability measurements for the PSS, however, were somewhat more puzzling. According to the arguments presented above, one should expect to see strongly correlated PSS values in the SJ task when the same group of observers are tested multiple times. Significant or near-significant correlations in SJ were found across Experiments 2 and 3; however, when observers' data were randomly split into two halves in Experiment 3, the TOJ tasks showed stronger correlations for the PSS between each of the two halves compared to SJ. Interestingly, correlations of the response bias between the two halves were not significant, indicating that it does not fully account for the strong PSS correlations. Our present analyses do not reveal what additional factors may drive these significant PSS correlations in TOJ, and more data from future research will be needed to justify these particular results. Nonetheless, since PSS correlations in the SJ task showed relatively high correlations, we believe that it is the more ideal method of measuring the PSS as it should be unaffected by any decisional biases when observers make responses.

Tactile-leading PSS values

A curious finding from the present experiments was that the PSS was always tactile-leading, while vision-leading PSS values are usually reported in the literature. This result can be attributed to the vision-first response bias in the TOJ task, but this bias does not exist in the SJ task. In order to investigate the cause of our tactile-leading PSS values, we manipulated the spatial distance between the visual and tactile stimulus in Experiment 2 (to test for a prior entry effect of the visual modality) and the certainty of stimulus location in Experiment 3. Neither of these manipulations was able to reverse the location of the PSS to vision-leading, although the PSS showed a small shift towards vision-leading in Experiment 3. In Experiment 2, the results may have remained unchanged because we did not explicitly instruct observers to attend to one particular modality, or to attend to both modalities equally. Hence, we cannot know for certain whether a prior entry effect remained present in the data, or did not exist at all. Future studies should investigate the role of instruction on eliciting prior entry effects when observers are attending to multiple sensory modalities, and whether it will lead to changes in the PSS.

Experiment 3 yielded relatively more fruitful findings. In the TOJ tasks, the PSS shifted towards vision-leading both when the location of the tactile and the visual stimulus were made uncertain. Although we cannot make strong claims as these shifts were not statistically significant (and no PSS shifts were observed in the SJ tasks), we hypothesize two possible reasons for these observed shifts in the PSS that will be worth examining with more data in future research. First, studies have shown that a stimulus that is presented on the same side of space as a "cue" appears to be processed faster compared to when it is presented on the opposite side (e.g. Spence & Driver, 1997; Spence et al., 1998; see also Driver & Spence, 1998 for a review). In relation to this finding, PSS data from Spence et al. (2001) showed that the visual processing speed increased relative to tactile under conditions of divided attention, compared to attending to the left or right side of space. We speculate that when the visual and tactile stimulus are always presented from the same locations (i.e. when the locations are certain), visual processing speed will be faster compared to when one or both locations are uncertain, since the presentation of one stimulus always "cues" the presentation of the other stimulus in a similar region of space. When the location of the tactile stimulus was uncertain (divided between two locations), it may have slowed *visual* processing speed (i.e. caused a vision-leading shift in the PSS) because observers paid more attention to the tactile modality since the two modalities were non-predictive of the other; this interesting result remains to be investigated further. Although a similar argument could be made for when the location of the visual stimulus was made uncertain (that the *tactile* processing speed would have decreased), the visual processing speed may have also decreased in this case due to a second factor: observers may have perceived the visual stimulus in their peripheral vision instead of central vision. Past literature has provided evidence that the processing speed in peripheral vision is slower than that in central vision (e.g. Tynan & Sekuler, 1982; Loke & Song, 1991) as it may require additional cortical structures (Prado et al., 2005), which could have been the reason for a vision-leading shift of the PSS rather than any attentional factors. It will be interesting for future research to examine the effect of multiple stimulus locations in individuals with hearing impairments, since they may have faster-than-typical peripheral processing speeds (Loke & Song, 1991).

Concerns about exclusion criteria

One remaining issue that may contribute to the findings from SJ and TOJ tasks is the exclusion of participants. Although it is common for some participants to be identified as outliers and excluded in studies that utilize the SJ and TOJ tasks, exclusion criteria, and therefore exclusion rates, differ across studies in the literature (e.g. Spence et al., 2001; Spence et al., 2003; Zampini et al., 2005a; Poliakoff et al., 2006; van Eijk et al., 2008; van Eijk et al., 2010; Love et al., 2013; Matthews et al., 2016) and some studies did not exclude participants at all (e.g. Schneider & Bavalier, 2003; Fujisaki & Nishida, 2009; Noel et al., 2015; Machulla et al., 2016). The exclusion criteria used in the present study were developed based on the belief that participants should be able to correctly judge the synchrony and temporal order at the extreme SOAs (±500 ms, as well as 0 ms for SJ), and that weak performance at these SOAs indicated that either participants did not fully attend to the tasks or performance was so poor that fitting their data would not result in any meaningful analyses (i.e. they were outliers). This was true for most of our excluded participants; however, some participants who made only one additional error outside the number that was allowed were kept in our dataset if their general performance otherwise appeared fine. Our exclusion criteria (and perhaps those used in previous studies) therefore do not encompass all of the variability for what should be considered valid data. Better fitting procedures may also exist for participants who perform poorly, which is important since they may have paid full attention but simply found the tasks very difficult, and should be included in the analyses of the experimental data. We leave it for future research to continue to examine the criteria that should be used to define the level of performance that actually reflects the range of human ability in the SJ and TOJ tasks.

Conclusion and Future Directions

We believe that the results from the present experiments indicate that the TOJ task provides a more accurate measure of the sensitivity in timing judgments, as the nature of the task appears to push observers to achieve their best possible temporal resolution. The task would be useful for studies where measuring the sensitivity is the primary objective, such as those investigating the crossed-hands deficit (e.g. Shore et al., 2002). Conversely, the SJ task provides a more accurate measure of the PSS, since in TOJ the PSS is strongly influenced by response biases which are often exhibited by the observers. In areas of research such as temporal recalibration (e.g. Takahashi et al., 2008), where measuring the PSS constitutes the primary goal, the SJ task would be the more suitable choice.

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