The visuotactile temporal binding window widens with spatial congruency

Bora Celebi[1] [0000-0002-8208-6068] , Müge Cavdan[1] [0000-0003-3575-3849] and Knut Drewing[1] [0000-0001-6161-5912]

[1] Justus-Liebig University, Gießen, 35394, Germany
bora.celebi@psychol.uni-giessen.com

Abstract. Signals from different senses are integrated into multisensory events or segregated according to their temporal and spatial relations. If signals are integrated, we perceive synchrony between them even in the presence of slight stimulus onset asynchronies (SOA). The range of SOAs during which physically asynchronous signals are perceived to be synchronous is called the temporal binding window (TBW). The TBW depends on various factors. Here we investigated how spatial congruency affects the width of the visuotactile TBW in a naturalistic setting, given that spatial congruency of signals in the single senses should promote multisensory integration and thereby binding. In a virtual reality (VR) environment, we presented visual and vibrotactile stimuli in different locations. Vibrotactile stimuli were presented on the participants' hands or forearms, and visual stimuli were rendered in real time on virtual counterparts of the tracked hands or forearms. We varied SOAs between vision and touch and asked if visual and tactile stimuli had occurred synchronously. Similar to what has been found in the audiovisual domain, the temporal binding window was wider when visual and tactile stimuli were spatially congruent— possibly due to enhanced multisensory integration. Thus, we extend the previous findings and conclusions on spatial congruency effects to visuotactile interactions in VR environments.

Keywords: Visuotactile synchrony, temporal binding window, virtual reality

1 Introduction

When a ball touches our hand and lights up at the same moment, we assume that touching and lighting up are related to each other. This constitutes one event that involves both vision and touch. However, when touch and lighting do not co-occur in time, we do not necessarily bind these two events into one. Our brains integrate or segregate sensory information coming from different senses into coherent percepts according to their temporal and spatial proximity. Integrating information from different senses, i.e., multisensory integration [1–3], helps individuals to create robust percepts [3]. These percepts have a higher sensory reliability than at least one of its counterparts which results in enhanced clarity and saliency [3, 4].

We perceive signals from different modalities as synchronous in the presence of slight stimulus onset asynchronies (SOAs) [2]. Multisensory integration also promotes the perception of synchrony leading to an increased number of synchrony judgements even within larger SOAs [4–6]. The magnitude of the temporal range of SOAs between signals that are judged to be synchronous with probabilities above 50 % defines the so-called temporal binding window (TBW) [5, 7, 8]. The TBW indicates a tolerance zone for the SOAs. This window is affected by different factors such as the sensory modalities involved, complexity of the stimuli, the environment, recalibration and training [9, 10]. The width of the TBW differs, e.g., between audiotactile, visuotactile, and audiovisual pairings [11–14]. Also, information complexity modulates the TBW; the TBW is smaller for simple stimulus pairs such as flashes and beeps as compared to more complex stimuli like speech [15, 16]. For example, the width of the TBW for simple flash and beep pairs has been found to be ~300ms, whereas it was larger, ~450 ms, for more complex audiovisual speech stimuli [15]. Additionally, the TBW depends on the environment, e.g., virtual reality (VR) [17]. In visuotactile judgements, a TBW of ~90 ms between a simple light and a vibration can be enough for participants to start detecting asynchrony, while a visuotactile TBW needs to be much larger (~200 ms) to detect asynchrony in a VR environment [11, 17].

Enhanced multisensory integration occurs when sensory signals from different modalities spatially coincide [18]. This is behaviorally manifested as decreased reaction times and increased task performance when the two stimuli of a pair are placed closely [19]. Multisensory integration increases probability of unity judgments on two signals from different modalities. The unity assumption essentially reflects the observers' belief that the two signals belong together and are bound [20]. Thus, spatial congruency favors the binding of two signals into a coherent percept and benefits the behavioral performance. In the temporal domain, spatial congruency of audiovisual and visuotactile pairs has been shown to decrease sensitivity in temporal order judgements [6, 21, 22]. In an audiovisual temporal order judgement task, Keetels and Vroomen [22] presented participants with auditory and visual stimuli from the same or different locations. They found that participants were more precise (smaller Just Noticeable Differences) when the stimuli were misaligned. This effect was explained by multisensory integration: collocated stimuli are more likely to be perceived as a single integrated event, making the temporal order of the two stimuli harder to judge. Similarly, Zampini and colleagues [6] presented participants audiovisual pairs with different SOAs and from different locations in a synchronicity judgement task. When auditory and visual stimuli were spatially congruent, the probability of synchronicity judgements increased. Overall, these studies suggest that when stimuli from visual and auditory modalities originate from the same location, they are more likely to be judged as synchronous hinting at a multisensory integration process.

Previous research investigated how TBW changes in different environments and conditions with simple visuotactile pairs [17, 23, 24]. Furthermore, the literature shows that spatial congruency in audiovisual pairs affects this window as spatial congruency have been shown to enhance multisensory integration. However, the effect of spatial congruency on TBW has not been investigated in visuo-tactile pairs . Here, we studied whether also the visuotactile temporal binding window would change with the spatial congruency between the signals. We conducted an experiment where we presented tactile and visual stimuli with varying SOAs and from two different locations in a VR environment with hand tracking. The VR setup with hand tracking was used to render a naturalistic setting which enabled participants to see their own movements as the enhanced presence in virtual environments could promote multisensory integration [25]. Also, we were able to approximately match the positions of visual and tactile stimuli as both of them were “on top of” the arms. We asked participants to judge if the visual and tactile stimuli were synchronous.

2 Methods

2.1 Participants

We recruited 25 participants (20 females, age range: 20-27, $M = 22.5$, $SD = 2.1$) through a circular email at Justus-Liebig University, Giessen. The sample size fits the result from a power analysis for a one-tailed paired t-test with a power of 80 % and an approx. medium effect size (d = .52).None of the participants reported any somatosensory impairments and all reported having normal or corrected-to-normal vision. Participants were compensated 8€/h or course credit for their time. They provided written informed consent prior to the experiment. Experimental procedures were approved by the local ethics committee of Justus-Liebig University, Giessen, LEK FB 06, in accordance with the Declaration of Helsinki without preregistration [26].

2.2 Stimuli and Apparatus

Vibrotactile Eccentric Rotating Mass (ERM) actuators were used to deliver vibrotactile stimuli (Vybronics, Ltd.) driven by a haptic motor driver DRV2605L (Texas Instruments Ltd.). The actuators were controlled by an Arduino board that communicates with the experiment program through the serial port. Visual environment and stimuli were displayed through a HTC Vive Pro Eye (HTC Inc.) VR headset at 90 Hz using a custom-made Unity (Unity Version 2021.2.7f1, Unity Technologies Inc.) script. Participant’s hand and forearm movements were recorded through a motion capture device Leap Motion (UltraLeap Inc.) and subsequently shown in the visual environment in real-time through a hand and arm model with a fixed size. The visual environment consisted of a white plane under the participants’ hands and a white canvas in front. A fixation cross was presented throughout the experiment in the midline between the left and the right hand of the participant. However, the location of the fixation cross did not change according to the hand movements. Participants were seated in front of a table where they put their hands and forearms and the motion capture device was located approximately 20 cm above their hands (see Fig. 1). Responses were collected using a pedal placed under the participant’s feet.

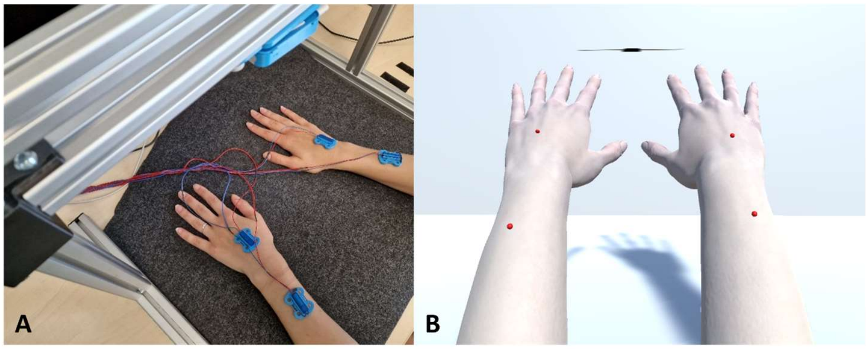

Fig. 1. A) Actuator locations and setup where participants placed their hands. B) Visual analogues of participants' hands in the virtual environment with all possible locations of the visual stimuli.

Vibrotactile stimuli consisted of a 99 ms vibration at the amplitude 3.48 m/s² root mean square (RMS). Two actuators were placed on each arm, one of which was located at the middle of the back of the hand and the other was placed at one-third of the distance between the carpus and the elbow away from the carpus. The distance between two locations on the arms was approximately 15 cm. Visual stimuli consisted of a red sphere with a radius of 2 cm and placed spatially aligned with the vibrotactile actuators on the visual hand and forearm. The duration of the visual stimuli was also approximately 99 ms (9 frames). To measure the potential delay in vibrotactile stimulation, we developed a procedure where a brief vibration was actuated after a button press. We recorded the button press and the vibration through a microphone 10 times The results show an average delay of 28.2 ms . The delay for a visual presentation with the same headset and software has been shown to be 31.3 ms [27]. Thus, there was no inherent latency difference between vibrotactile and visual stimuli. On each trial, visual and vibrotactile stimuli were presented from only one of these locations at the same arm.

2.3 Design and Procedure

In the experiment, we manipulated the SOAs between visual and vibrotactile stimuli (-297, -198, -99, 0, 99, 198, and 297 ms, negative SOAs indicate that the visual stimuli was first), vibrotactile location (hand or forearm), and visual location (hand or forearm). As a result of varying locations, in half of the trials vibrotactile and visual stimuli were congruent and in the other half they were incongruent. Additionally, in half of the trials, both stimuli were presented on the left arm, and in the other half on the right arm. Each combination of SOA (7), locations (2 × 2), and arm (2) was repeated 12 times which resulted in a total of 672 trials. The trials were presented in a completely random order. Prior to the experiment, participants completed a training session that included the same conditions with 2 repetitions.

At the beginning of the experiment, we calibrated the virtual arm locations once the participants were seated. The experimenter changed the location of the virtual arms and asked the participant to place them in a location where they feel the virtual hands and forearms to be spatially aligned with the real hands' and forearms' locations. The experiment started with the training session. On each trial, participants were first presented with a visual and a vibrotactile stimulus. Following 500 ms after the offset of the second stimulus, a question appeared on the white canvas in the visual environment, asking whether the tactile and the visual stimulus had been synchronous. Participants had 5 seconds to respond to the question through foot pedals (left pedal: "Yes", right pedal: "No"). 500 ms after the response, the next trial started. The experiment lasted around 40 minutes.

2.4 Data Analysis

Frequently, data from simultaneity judgement tasks has been fitted with a Gaussian function because of its ability to capture the data well [4]. However, this approach does not take into account that the presence of two signals (here visual and vibrotactile) can give rise to two different arrival times and possibly criteria [28, 29]. The difference in arrival times may come along with different mechanisms on how to decide about synchronicity depending on which signal comes first [28]. Therefore, here, we applied an observer model that assumes different synchronicity criteria for each temporal order of stimuli [30, 31]. The model uses a psychometric function, essentially representing the difference between two different cumulative Gaussians for the visual preceding (VP) and tactile preceding (TP) sides of the synchrony;

$$p_{\mathrm{synchronous}} = \phi(C_{VP}, SOA, \sigma_{VP}) - \phi(C_{TP}, SOA, \sigma_{TP}) \tag{1}$$

where ϕ is the cumulative Gaussian function, C_{VP} and C_{TP} are the decision criteria for both temporal orders (visual and tactile sequentially) and σ_{VP} and σ_{TP} represent the variability in the criteria and arrival times. $p_{\mathrm{synchronous}}$ represents the proportion of responses 'synchronous' in each condition. Variability parameters have been argued to correspond to a combination of sensory noise and criteria noise [28]. Thus the model consists of 4 free parameters (C_{VP} , C_{TP} , σ_{VP} , σ_{TP}). The width of the TBW is determined by calculating the absolute difference in SOAs between the points where the probability of a 'synchronous' response is 50% for both sides of the function. This equates the sum of the absolute value of the two criterion parameters C_{TP} and C_{VP}. Thus, the width of the TBW is directly derived from the criteria (see Fig. 2A).

Next, we fitted this function to each congruency condition for each participant using maximum likelihood estimation with binomial likelihoods [32] and optimized with Nelder-Mead simplex search [33]. Finally, we submitted these values to a *t*-test and ANOVA to statistically test the effect of congruence and temporal order.

3 Results

We computed the mean coefficient of determination (R^2) of the fits across participants and conditions computed as squared spearman correlation coefficient to assess the goodness of fit. The mean R^2 was .88 (*SD*: .11). The mean of the criterion parameters (C_{TP} , C_{VP}) was 227.5 ms (*SD*: 44.6, range: 102.7 -300) and the mean of the variability parameters (σ_{TP} , σ_{VP}) was 138.1 ms (*SD*: 50.7, range: 61.2 -222.2). Mean values for each participant in each condition were computed for the further statistical analyses. We conducted a one-tailed paired samples *t*-test to investigate the predicted effect of congruence on the width of the temporal binding window. The temporal binding window was significantly wider in the congruent conditions than in the incongruent conditions $t(24) = 3.6$, $p < .001$, $d = .31$ (see Fig. 2B).

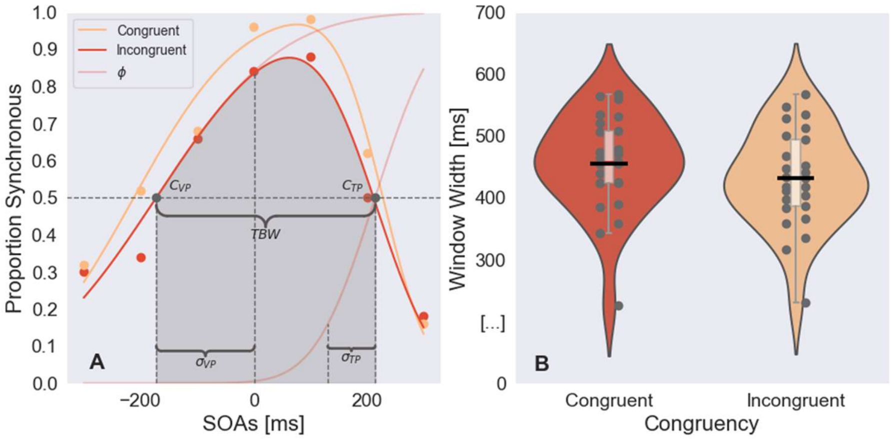

Fig. 2. A) Example demonstration of the model function fitted to an example participant's data. Negative SOAs depict visual preceding conditions while positive ones depict tactile preceding ones. Semi-transparent colored lines correspond to the representative cumulative Gaussians for each temporal order. The criterion (C_{TP} , C_{VP}) and variability (σ_{TP} , σ_{VP}) parameters are shown for each temporal order. The temporal binding window (TBW) is depicted as the dark gray area. B) The width of the temporal binding window for congruent and incongruent conditions. Gray dots indicate individual data points and the white box indicates the interquartile range (IQR). Whiskers on each side present 1.5 IQR and the black line represents the mean. A normal gaussian is used as kernel density function for smoothing the violin plots.

Then, we submitted criterion values (C) for each temporal order (visual preceding, tactile preceding) and congruency to a repeated measures ANOVA. Congruency had a significant main effect $F(1, 24) = 12.96$, $p = .001$, partial $\eta^2 = .35$, confirming that criteria for synchronicity were less strict when the signals were spatially congruent. Nor the main effect of temporal order $F(1, 24) = .39$, $p > .534$, partial $\eta^2 = .01$ neither the interaction between congruency and temporal order $F(1, 24) = .75$, $p > .955$, partial η^2

$< .01$ were statistically significant (see Fig. 3A), suggesting that the criteria did not considerably depend on whether the tactile or the visual stimulus was presented first.

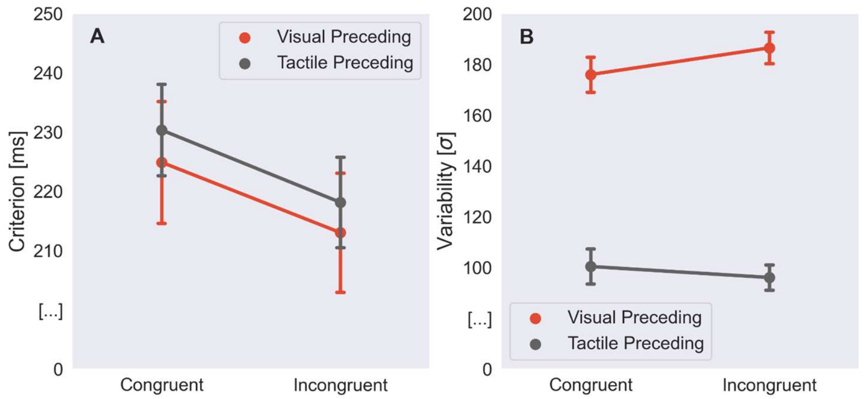

Fig. 3. A) Criterion values for temporal order and congruency conditions. B) Variability values for temporal order and congruency conditions. Error bars depict standard error of the mean.

In order to test if the shape of the function is influenced by congruency and temporal order, we conducted a repeated measures ANOVA on variability (σ). Temporal order had a significant effect: $F(1, 24) = 180.57$, $p < .001$, partial $\eta^2 = .88$, indicating that the variability was larger when the visual stimulus was first compared to when the tactile stimulus was first. Further, there was a significant interaction effect $F(1, 24) = 4.50$, $p = .044$ partial $\eta^2 = .15$. Although the difference between congruency conditions in the visual preceding temporal order was greater than the difference in the tactile preceding tactile order, this effect was rather small. However, there was no significant effect of congruency $F(1, 24) = 0.88$, $p > .355$, partial $\eta^2 = .05$ meaning that variability did not depend on spatial congruency (Fig. 3B).

4 Discussion

In this study, we examined how the visuotactile temporal binding window is affected by the spatial congruency between signals in a VR environment. We found that the TBW gets wider when the two signals coincide in space. Previous studies have demonstrated that people are more likely to integrate spatially congruent signals, and for audiovisual pairings it has been shown that the resulting multisensory integration increases the probability to perceive synchrony despite physical asynchronies. Our results suggest that these mechanisms also apply to visuo-tactile pairings in a virtual environment. Interestingly, the variability of the decision criterion for synchrony was much higher when the visual stimulus was presented first as compared to when the tactile stimulus was first, which we discuss further. Notably, overall the criteria were less strict, i.e., the width of the TBW was larger than in previous studies which could be related to the complexity differences in the environments [12, 13, 15].

Visuotactile SOAs required to detect asynchronies between two signals have been found to be much smaller in previous studies conducted with rather less complex laboratory environments [12, 13]. For instance, Vogels [12] found the width of the TBW to be around 90 ms with simple visuotactile pairs on the finger. We argue that the larger TBW in the current study relates to stronger multisensory integration. Here we employed a relatively complex VR environment where we presented participants with the virtual analogues of their hands with full hand tracking. We did thus not only exactly match locations of the vibrotactile stimulation to that of the visual stimuli in world coordinates, but through the virtual environment we also convincingly matched the location relative to the perceived body – increasing immersion. This idea is supported by the fact that even a simple drawing of a visual analogue of a hand affects temporal judgements and increases the integration likelihood of visual and tactile stimuli [34]. We argue that the implementation of a realistic body reference in VR including the use of hand tracking promoted multisensory integration which likely resulted in visual and tactile signals being unified in larger temporal windows – even in the incongruent conditions.

The variability of the decision criterion for synchronicity was higher when the visual stimulus was first as compared to when the tactile stimulus was first (Fig. 3B). This difference is in line with the literature that suggests the presence of different mechanisms in synchronicity judgment depending on the temporal order of stimuli in different senses [28, 35]. The variability parameters of the decision criteria actually do comprise both sensory noise and criterion noise at the same time. However, sensory noise should be similar in both temporal order conditions, so the difference between conditions likely reflect the differences in proper criterion noise [28]. Thus, our results suggest that participants showed a larger trial-by-trial variance in setting their synchronicity criterion in the visual preceding condition compared to in the tactile preceding condition. We hypothesize that the vibrotactile stimulus was more salient than the visual one, because the vibrotactile stimulus is presented on the body itself and thereof automatically captures attention, whereas the visual stimulus requires directing of spatial attention [36]. Consequently, noticing the visual cue in the visual preceding condition comes along with some initial variability in the perception of the start time, which adds up to the resulting criterion variability. In contrast, in the tactile preceding condition, the start of the visual signal is predicted and attention can be directed to vision in advance without producing extra variability. However, future studies are required to test this hypothesis.

We found that spatial congruency increases the width of the visuotactile TBW (Fig. 2B). Previous research in the audiovisual domain had already shown that the TBW increases and temporal order judgements become less sensitive with audiovisual spatial congruency [6, 21, 22]. Thus, our results extend the effects of spatial congruency on the TBW to visuotactile interactions in VR. It is known that spatial congruency between stimuli enhances multisensory integration in certain tasks and conditions [18], because it increases the probability of judgments on the unity of the two constituting signals [20]. Consequently, we can assume that also here, congruency of visual and vibrotactile signals promoted the integration process. Specifically, participants might be more likely to bind the two signals into one coherent percept, resulting in a higher tendency for the perception of synchrony, particularly for the used visuo-tactile pairs. In other words, we assume that it was harder to segregate the timings of visual and tactile stimuli because spatial congruency of the pair favored unifying them. A similar explanation can also be phrased in terms of the causal inference framework. This framework posits that when faced with two stimuli, we preliminarily judge whether they come from a common cause or independent ones [37, 38]. Spatial congruency, within this framework, increases the likelihood of perceiving a common cause which in turn binds these two stimuli and aligns judgements on them. Here, we argue that spatial congruency between visual and tactile stimuli could have promoted the hypothesis of a common cause. To conclude, spatial congruency of the visual and tactile signals poses a critical role in shaping temporal judgements possibly by increasing the likelihood of multisensory integration.

This study examined the interplay between temporal and spatial characteristics of visuotactile stimuli in specific locations – both presented on the top side of the hand and the forearm. We showed that in visuotactile pairs, the TBW gets wider with spatial congruency between the constituting signals. It is however crucial to note for the application of these results that the width of the temporal binding window strongly varies with various factors including location, complexity of stimuli, and task [15]. Thus, the exact width of the binding window can realistically be estimated for different conditions and locations, only by studying it under the specific circumstances. Nevertheless, applications that require temporally desynchronizing or aligning visual and tactile representations could benefit from our findings. In virtual reality applications where synchronization of tactile and visual feedback profoundly influences user immersion, employing a realistic temporal binding window can enhance the effectiveness of the stimulations consequently improving the realism.

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