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Temporal limits on rubber hand illusion reflect individuals' temporal resolution in multisensory perception

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ABSTRACT

Synchronous, but not asynchronous, multisensory stimulation has been successfully employed to manipulate the experience of body ownership, as in the case of the rubber hand illusion. Hence, it has been assumed that the rubber hand illusion is bound by the same temporal rules as in multisensory integration. However, empirical evidence of a direct link between the temporal limits on the rubber hand illusion and those on multisensory integration is still lacking. Here we provide the first comprehensive evidence that individual susceptibility to the rubber hand illusion depends upon the individual temporal resolution in multisensory perception, as indexed by the temporal binding window. In particular, in two studies we showed that the degree of temporal asynchrony necessary to prevent the induction of the rubber hand illusion depends upon the individuals' sensitivity to perceiving asynchrony during visuo-tactile stimulation. That is, the larger the temporal binding window, as inferred from a simultaneity judgment task, the higher the level of asynchrony tolerated in the rubber hand illusion. Our results suggest that current neurocognitive models of body ownership can be enriched with a temporal dimension. Moreover, our results suggest that the different aspects of body ownership operate over different time scales.

1. Introduction

Body representation has been linked to the processing and integration of multisensory signals (for reviews: Blanke, 2012; Ehrsson, 2012). An outstanding example of the pivotal role played by multisensory mechanisms in body representation is the Rubber Hand Illusion (RHI; Blanke, 2012; Botvinick & Cohen, 1998; Ehrsson, 2012). This illusion is generated when temporally close visual and tactile events occur on a visible rubber hand and the hidden participant's hand. The typical procedure has a participant sit with a visible fake (rubber) hand in front of them and her real hand under a curtain (not visible) while an experimenter uses a pair of paintbrushes to simultaneously stroke the rubber hand and the hidden-real hand. The illusion typically elicits a feeling of "ownership" of the rubber hand. The RHI does not arise when visual and tactile stimuli are out of synchrony, with a stimulus offset larger than 300 ms (Bekrater-Bodmann et al., 2014; Shimada, Suzuki, Yoda, & Hayashi, 2014).

Based on this temporal constraint and evidence showing that RHI is associated with neural activity in multisensory brain areas (Blanke, 2012; Ehrsson, Holmes, & Passingham, 2005; Ehrsson, Spence, & Passingham, 2004; Ionta, Martuzzi, Salomon, & Blanke, 2014; Makin, Holmes, & Ehrsson, 2008; Tsakiris, Hesse, Boy, Haggard, & Fink, 2007), it has been assumed that RHI depends upon multisensory integration processes (Blanke, 2012; Ehrsson, 2012). Hence, temporal constraints of RHI would reflect those characterizing multisensory processing. Indeed, seminal studies in animals showed that multisensory integration is more likely to occur when the constituent unisensory stimuli arise synchronously or over a short temporal interval called temporal window of integration (or Temporal Binding Window, TBW; Colonius & Diederich, 2004; Vroomen & Keetels, 2010; Wallace & Stevenson, 2014). The most established paradigm used to study the multisensory temporal binding window is the simultaneity judgment task (Vatakis & Spence, 2006), in which participants judge the perceived simultaneity (i.e., the synchrony) of paired stimuli.

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Despite the common temporal features between multisensory integration and the RHI, there is no empirical data supporting the dependency of the RHI upon the temporal resolution of multisensory integration mechanisms.

Starting from this gap in the literature, we seek to provide the first comprehensive evidence linking individual susceptibility to the RHI to individual temporal resolution in multisensory perception (i.e., the TBW). Indeed, they are both characterized by marked interindividual differences (Asai, Mao, Sugimori, & Tanno, 2011; Stevenson, Zemtsov, & Wallace, 2012).

Previous researches have already shown that varying the Stimulus Onset Asynchrony (SOA) between the visual stimulus delivered on the rubber hand and the tactile stimulus delivered on the real hand has consequences on the strength of the RHI. For instance Shimada and colleagues (Shimada, Fukuda, & Hiraki, 2009) investigated delays up to 600 ms in steps of 100 ms. The authors found that illusion ratings were significantly higher for short delays, up to 300 ms. In the present study we do a step forward by formally associating sensitivity to the rubber hand illusion to temporal sensitivity in multisensory integration. Such a finding would foster new investigations into the temporal unfolding of body ownership, an issue largely neglected so far.

In order to achieve this, we measured participants' TBWs through the use of a simultaneity judgment task, employing visual and tactile stimuli. Next, in the same participants, and employing the same stimuli, we measured susceptibility to the RHI in the synchronous and asynchronous conditions. Importantly, in the asynchronous condition we individualized the amount of asynchrony (i.e. Stimulus Onset Asynchrony, SOA) between the visual and the tactile stimuli, based on the individuals' TBW. This means that the individuals' own TBW was used to establish the asynchrony between the visual stimulus delivered on the rubber hand and the tactile stimulus delivered on the participants' real hand. In more details, rather than using standard large asynchronies, as used in previous research (Tsakiris & Haggard, 2005) (usually up to 1000 ms), we selected, at the individual level, the SOA where the stimuli had 25% probability of being integrated. This allowed for direct coupling between the individual's temporal resolution in visuo-tactile multisensory integration and the temporal determinants by which touch can be attributed to a rubber hand. To this end, we used a new computer-controlled visuo-tactile stimulation for RHI. This is a methodological aspect that deserves mention. Previous studies on the RHI have either used manual stroking of the real and the rubber hands (for a review see: Costantini, 2014) or have used virtual reality. Here, instead, visual stimuli consisted on a LED attached on the dorsal surface of the index finger of a realistic prosthetic hand, while the tactile stimulus consisted on a mechanical tapper attached on the dorsal surface of the participants' index finger. This experimental setup allows accurate timing in the stimulation while keeping the environment more ecological that the one that could be achieved in virtual reality.

Based on the theoretical assumption of a dependency of the individual susceptibility to RHI upon the individual multisensory temporal binding window, our prediction was that even a small amount of asynchrony, but outside the individuals' TBW, is enough to prevent the experience of the RHI.

However, since we are using the individuals TBW to define the level of asynchrony to be used in the RHI, we cannot rule out a systematic bias that is inherent to this design. That is, it could be argued that individuals with a wide TBW are also more susceptible to the RHI based on a third, unaccounted for variable. In a second study we hope to buttress this by using a median spit method. That is, we recruited a new group of participants, and measured their TBW. Subsequently, we asked them to perform the RHI in the synchronous and asynchronous conditions. In this new study the level of asynchrony between the visual stimulus delivered on the rubber hand and the tactile stimulus delivered on the participants' hand corresponded to the median value of the TBW in the new sample. This procedure allowed us to use the same amount of asynchrony that was within the TBW of half the participants but outside the TBW of the others.

Again, based on the assumption of a dependency of the individual susceptibility to RHI upon the individual multisensory temporal binding window, we expect a difference between the synchronous and the asynchronous condition only in the latter group (where RHI is induced with a stimulus onset asynchrony greater than the individual temporal binding window).

2. Experiment 1

2.1. Participants

Thirty-seven participants (14 male, mean age = 21.2 years, SD = 6.2 years, range = 18–32 years) were included in the study. All procedures were approved by the Institute of Mental Health Research, University of Ottawa Review Board (REB No. 2014008). On the same day participants took part in two separate sessions. In the first session we measured the individuals' temporal binding window (via the simultaneity judgment task); in the second session we induced the RHI in synchronous and asynchronous conditions.

2.2. Simultaneity judgment task - stimuli and procedure

The experimental stimuli consisted of series of cross modal stimuli (1 visual and 1 tactile). Stimuli were delivered across hemispaces (1 tactile Left/1 visual Right or 1 visual Left/1 tactile Right). This was done to ensure that the spatial distribution of the stimuli in the simultaneity judgment task (SJ) resembled, as much as possible, the spatial distribution of visuo-tactile stimuli during the RHI. Stimuli were delivered sequentially with one of the following Stimulus Onset Asynchronies (SOA): ±350, ±200, ±120, ±70, ±40, ±25 ms. By convention, throughout the current article negative SOAs indicate a trial in which the visual stimulus was presented first, whereas a positive SOA indicates a trial in which the tactile stimulus was presented first. A total of 12 intervals were used, with 32 trials per interval. For balance, in half of the trials, left-sided stimuli preceded right-sided stimuli, and vice versa for the other half. The intertrial interval (ITI) ranged between 2000 and 3000 ms. The presentation of the stimuli was pseudorandomized. Visual stimuli consisted of two red light-emitting diodes (LEDs; with a 0.5 cm diameter) fixed on a table and positioned at 4 cm Left and Right of a central fixation point (subtending 4° of visual angle, see Fig. 1) with a luminance of 0.48 lm. Visual stimuli lasted 30 ms.

Tactile stimuli were delivered by means of two miniature solenoid tappers (MSTC3; M & E Solve, www.me-solve.co.uk) attached to the dorsal surface of the middle fingers. The solenoids produced a supra-threshold vibrotactile stimulus oscillating at 100 Hz for a total duration of 30 ms.

Participants were seated in a dimly lit room with their corporeal midline aligned with a fixation point located 57 cm from the plane of their eyes, with their right and left index fingers resting on two response buttons located on a table. Each hand was in its homonymous hemispace, close to each LED (see Fig. 1). Participants were asked to focus on a fixation cross that was placed half way between the response buttons at all times.

The task was a simultaneity judgment, used to derive the TBW. In this task, participants were presented with a series of visuo-tactile stimuli at the above-defined SOAs. The participants were asked to report whether each presentation occurred at the same