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Asymmetries in visuomotor recalibration of time perception: Does causal binding distort the window of integration?

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ABSTRACT

The recalibration of perceived visuomotor simultaneity to vision-lead and movement-lead temporal discrepancies is marked by an underlying causal asymmetry, if the movement (button press) is voluntary and self-initiated; a visual stimulus lagging the button press may be interpreted as causally linked sensory feedback (intentional or causal binding), a leading visual stimulus not. Here, we test whether this underlying causal asymmetry leads to directional asymmetries in the temporal recalibration of visuomotor time perception, using an interval estimation paradigm. Participants were trained to the presence of one of three temporal discrepancies between a motor action (button press) and a visual stimulus (flashed disk): 100 ms vision-lead, simultaneity, and 100 ms movement-lead. By adjusting a point on a visual scale, participants then estimated the interval between the visual stimulus and the button press over a range of discrepancies. Comparing the results across conditions, we found that temporal recalibration appears to be implemented nearly exclusively on the movement-lead side of the range of discrepancies by a uni-lateral lengthening or shortening of the window of temporal integration. Interestingly, this marked asymmetry does not lead to a significantly asymmetrical recalibration of the point of subjective simultaneity or to significant differences in discriminability. This seeming contradiction (symmetrical recalibration of subjective simultaneity and asymmetrical recalibration of interval estimation) poses a challenge to common models of temporal order perception that assume an underlying time measurement process with Gaussian noise. Using a two-criterion model of the window of temporal integration, we illustrate that a compressive bias around perceived simultaneity (temporal integration) even prior to perceptual decisions about temporal order would be very hard to detect given the sensitivity of the psychophysical procedures commonly used.

1. Introduction

Humans can recalibrate the perceived timing of multisensory events to compensate for the presence of small temporal discrepancies between the senses for a number of modality pairs, such as vision and audition or vision and touch (e.g., Di Luca, Machulla, & Ernst, 2009; Fujisaki, Shimojo, Kashino, & Nishida, 2004; Keetels & Vroomen, 2008; Roach, Heron, Whitaker, & McGraw, 2011; Yarrow, Jahn, Durant, & Arnold, 2011). The perceived temporal order of a voluntary movement (e.g., a button press) and a sensory stimulus (e.g., a visual flash) is no exception from this (Heron, Hanson, & Whitaker, 2009; Keetels & Vroomen, 2012; Rohde & Ernst, 2013; Stetson, Cui, Montague, & Eagleman, 2006; Sugano, Keetels, & Vroomen, 2010; Sugano, Keetels, & Vroomen, 2012). This means that a participant accustomed to the presence of systematic delay between such a button press and a visual flash will adjust his or her perception of perceived simultaneity of these events to partially compensate for the lag. It also means that participants who have undergone such adaptation will perceive visual stimuli as preceding a button press, even when they physically occur shortly afterwards. As some researchers observed (Heron et al., 2009; Rohde & Ernst, 2013; Stetson et al., 2006), this shift in perceived temporal order violates the underlying causal structure of this kind of scenario, i.e., that a cause (voluntary button press) has to precede its effect (the visual flash). If voluntary action is involved, there is thus a causal asymmetry around the point of actual simultaneity, an asymmetry that is not present when passively perceiving the temporal order in different modalities, such as a visual flash and an auditory click.

The assumption of a causal link between an action and a sensory event has been shown to distort time perception (compression of perceived timing between motor and visual events; intentional or causal binding, e.g., Buehner & Humphreys, 2009; Haggard, Clark, &

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J,K., 2002; cf. also Eagleman & Holcombe, 2002). Intentional binding likely contributes to the unity assumption (Welch & Warren, 1980), which is a prerequisite for multisensory integration. Integration typically requires stimuli to occur in close temporal proximity, i.e., they should fall within a window of integration (e.g., Bresciani et al., 2005; Shams, Kamitani, & Shimojo, 2000). Intentional or causal binding should only occur for discrepancies where movement leads the temporal order, that is, in cases when participants have a subjective sense of agency (Rohde, Scheller, & Ernst, 2012). Thus, if movement events are produced voluntarily, this could lead to asymmetries in the processing or recalibration of visuomotor time perception due to an asymmetrical window of integration. The competing hypothesis is that recalibration is symmetrical. For instance, Cai, Stetson, and Eagleman (2012) proposed a neural model, where visuomotor temporal recalibration is implemented as the temporal analog of the motion after-effect. If temporal discrepancies are treated just as spatial discrepancies, recalibration will not be expected to be sensitive to the direction of a discrepancy.

In a previous study, we tested whether there are asymmetries in the recalibration of perceived visuomotor simultaneity using a voluntary button-pressing task. To this end, we trained participants in different blocks to the presence of vision-lead and movement-lead temporal discrepancies between the voluntary button press and a flash (Rohde & Ernst, 2013). Using a temporal order judgment (TOJ) paradigm, we compared the amount by which the point of subjective simultaneity (PSS) shifts as a result of recalibration. To our surprise, we found no evidence for an asymmetry; in a relatively short time frame, participants recalibrated for 20–25% of the training discrepancy equally in both directions (movement-lead and vision-lead).

Using a TOJ task, however, we could only determine changes in time perception around the one point of perceived simultaneity, not along the entire range of perceived temporal intervals between a button press and the visual flash. Shifts in PSS in temporal recalibration studies do not always generalize across the entire range of stimulus onset asynchronies (SOAs). For instance, Yarrow et al. (2011) recently showed, using an audiovisual SJ temporal recalibration paradigm, that temporal recalibration is better modeled as a uni-lateral expansion of the window of perceived simultaneity, on the side of the trained discrepancy only. This non-linearity in recalibration is not captured in TOJ paradigms (Yarrow et al., 2011). Similarly, Roach et al. (2011) have used an interval estimation (IE) paradigm to study audiovisual temporal recalibration. They observe non-linear distortions in the perceived timing of visuoauditory intervals after temporal recalibration, i.e., recalibration was stronger for short intervals (close to perceived simultaneity) and less pronounced for long intervals. Again, these distortions are of a nature that TOJ paradigms cannot detect (cf. Roach et al., 2011).

In order to illustrate what information the different psychophysical tasks provide with respect to the temporal interval perception between sensory signals, Fig. 1 depicts a common model for simultaneity judgment (SJ), TOJs, and IEs (the model is adapted and extended from Yarrow et al., 2011). The grey identity line shows the relationship between physical and perceived asynchrony, which, for simplicity, we assume to be veridical and thus a linear function with slope = 1. Furthermore, we assume that the asynchrony estimates are not perfect but corrupted by Gaussian noise (blurred diagonal). In this model, IE judgments would intuitively be expected to reproduce the blurred diagonal itself. A TOJ involves the perceptual decision about whether a stimulus occurred before or after the other (sensed SOA = 0 implies perceived simultaneity), which results from integrating the probability that the sensed asynchrony for a given SOA is above or below 0. This yields a cumulative Gaussian function (Fig. 1A and B, inlay).

The probability distribution of SJ responses is often not quite correctly modeled as a Gaussian probability distribution (cf. Vroomen & Keetels, 2010; also discussion in Yarrow et al., 2011), which roughly corresponds to a cross section through this blurred diagonal (Fig. 1A). Cravo, Claessens, and Baldo (2011) and Yarrow et al. (2011) recently proposed that SJs should be better modeled as a two-criterion decision process. A window of simultaneity is defined between two criteria μ_V and μ_M. The probability of perceiving simultaneity then is the integrated probability of a registered SOA falling between these two criteria, i.e., the difference between the two cumulative Gaussian functions flanking this window (bell-shaped curve in Fig. 1B inlay). That is, even with Gaussian distributed noise on the interval estimates, the resulting SJ curve will not be Gaussian, which becomes more apparent the further apart the two criterions are set.

How is temporal recalibration realized in such a model? The PSS shifts observed in TOJ paradigms imply that the mid-section of the diagonal (around the sensed SOA = 0) is shifted sideways into the direction of the adapted SOA. This would lead to a shift in the cumulative Gaussian function for temporal order perception. The simplest possible way of generalizing such temporal recalibration of the mid section across the range of SOAs would be a shift in a set point, which would mean that the entire blurry diagonal is shifted along with the PSS (cf. Fig. 2A). However, the mentioned results on non-linear recalibration (Roach et al., 2011; Yarrow et al., 2011) show that this is not the case in audiovisual temporal recalibration. Roach et al.'s (2011) results showed that the shift evident in the mid-section (recalibration of PSS) decreases as the size of SOAs grows, leading to a distortion in the IE profile (Fig. 2B). Yarrow et al.'s (2011) results showed that recalibration involves a uni-lateral widening of the window of simultaneity (criterion shift, Fig. 1B). Such phenomena concern the perception of intervals along the range of SOAs and are not captures in TOJ paradigms.

It is possible that similar to the audiovisual case, also in visuomotor temporal recalibration, distortions in the generalization of recalibrated time perception exist but go undetected by a TOJ task. To look for such

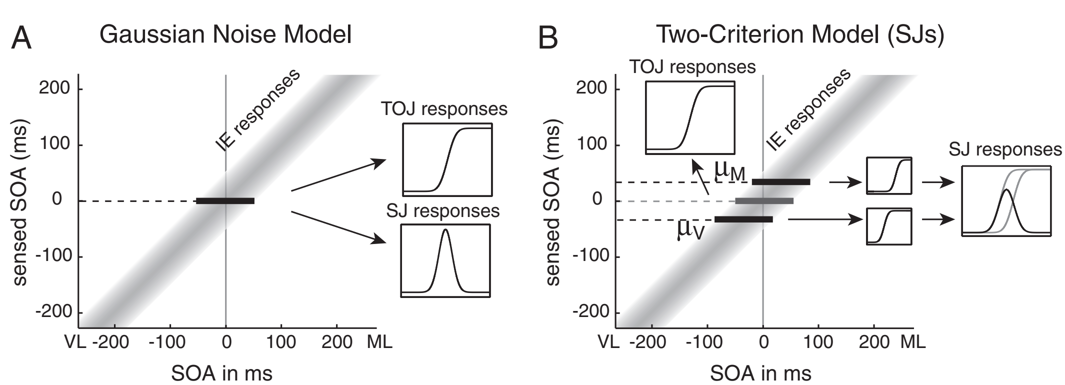

Fig. 1. Illustrations of statistical assumptions underlying models of time perception. (A) The Gaussian noise model. (B) The two-criterion model for SJs, which is an extension of the Gaussian noise model (Cravo et al., 2011; Yarrow et al., 2011). Illustrations are adapted from Yarrow et al. (2011).