Title: 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; a lagging visual stimulus 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 (IE) 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 significantly asymmetrical recalibration of the point of subjective simultaneity (PSS) or to significant differences in discriminability. This confirms an earlier study, where we found no significant evidence for directional asymmetries in recalibration of PSS using a temporal order judgment paradigm (Rohde & Ernst, 2013). This seeming contradiction in the results (symmetrical recalibration of PSS and asymmetrical recalibration of interval estimation) casts a new light on common models of temporal order perception. Using a two-criterion model of temporal integration, we illustrate that a compressive bias around perceived simultaneity (temporal integration) prior to perceptual decisions would be very hard to detect in the probability distribution of responses. This in turn means that integration may happen even before perceptual judgments about order, simultaneity and durations are made.

(Graphical abstract)

Highlights:

- Humans recalibrate visuomotor interval perception to the presence of temporal discrepancies.
- Recalibration is asymmetrical and occurs mostly for movement-lead stimuli.
- This is realized as one-sided compression or extension of the window of temporal integration.
- Changes in the point of subjectivity are, by contrast, symmetrical.
- A two-criterion model of temporal integration can resolve this seeming contradiction.

Keywords: time perception, temporal recalibration, visuomotor integration, multimodal perception, intentional binding

Classification codes

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., Fujisaki et al., 2004; Keetels & Vroomen, 2008; Di Luca et al., 2009; Roach et al., 2011; Yarrow et al., 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 (Stetson et al., 2006; Heron et al., 2009; Sugano et al., 2010; Keetels & Vroomen, 2012; Sugano & Vroomen, 2012; Rohde & Ernst, 2013). 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 this lag. It also means that participants who have undergone such training will perceive visual stimuli as preceding a button press, even when they physically occur shortly afterwards. As some researchers observed (Stetson et al., 2006; Heron et al., 2009; Rohde & Ernst, 2013), 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., Haggard et al., 2002; Eagleman & Holcombe, 2002; Buehner & Humphreys, 2009). 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., Shams et al., 2002; Bresciani et al. 2005). If intentional or causal binding only occurs for discrepancies where movement leads the temporal order, this could lead to asymmetries in 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 et al. (2012) propose 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 investigated whether the underlying causal asymmetry also leads to an asymmetry in the perception of simultaneity after visuomotor temporal recalibration. To this end, we trained participants in different blocks to the presence of vision-lead and movement-lead temporal discrepancies between a 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 this 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.

However, recent studies (e.g., Roach et al., 2011; Yarrow et al., 2011) have shown that an exclusive focus on PSS in temporal recalibration may not capture all aspects of temporal recalibration. Roach et al. (2011) have used an interval estimation (IE) task to study audiovisual temporal recalibration. Participants had to estimate the length of intervals between a visual and an auditory stimulus. This approach revealed non-linear distortions in the perceived timing of visual and auditory stimuli after temporal recalibration, i.e., recalibration was stronger for short intervals and less pronounced for long intervals. These distortions are of a nature that temporal order and simultaneity judgment paradigms (TOJ and SJ) cannot detect. Yarrow et al. (2011) could similarly show that audiovisual recalibration of SJs involves a widening of the window of simultaneity on the side of the trained discrepancy only.

In the current study, we used an interval estimation (IE) paradigm to investigate, whether there are asymmetries in visuomotor recalibration that a TOJ paradigm cannot detect. It is possible that, similar to the audiovisual case, distortions in the recalibration of visuomotor time perception exist but go undetected by TOJ or SJ tasks. Figure 1 depicts three possible scenarios of recalibration of visuomotor interval perception. Recalibration could be a *linear shift* with respect to baseline (A), a result that would be compatible with the explanation that recalibration involves a general update of a *differential delay*, without asymmetries due to intentional (causal) binding. Alternatively, there could be *local non-linear biases* in recalibrated time perception (B), similar to those that Roach et al. (2011) report for audio-visual recalibration. Even though this kind of recalibration is non-linear, it is still symmetrical along the negative diagonal, which would indicate that the mechanisms of recalibration are not sensitive to direction (i.e., which modality leads the temporal order in the trained discrepancy). A third option is that there are *asymmetries around the point of actual simultaneity*, either in processing (asymmetrical distribution of responses already in baseline condition) or in recalibration. Changes due to recalibration could, for instance, be more pronounced for movement-lead events (right side of the range in Fig. 1 C), where intentional binding can be expected to occur. Note that the shifts in PSS (intercept with dashed horizontal lines) are symmetrical for all three possible scenarios. The differences in shape can only be revealed using an IE paradigm.

In order to address this question, we tested human recalibration of perceived visuomotor simultaneity to vision-lead and movement-lead temporal discrepancies using an IE task. To be able to present visual stimuli even before a voluntary action (vision-lead temporal discrepancies), we used the same set-up as in earlier work (Rohde & Ernst, 2013), where the timing of a button press is predicted in real time from early onset of finger movement, which is continually tracked. Participants were trained in blocks to the presence of one of three visuomotor lags: 100 ms vision-lead (VL), 0 ms discrepancy (baseline, B), 100 ms movement-lead (ML). The differences in interval perception after recalibration were compared between conditions.

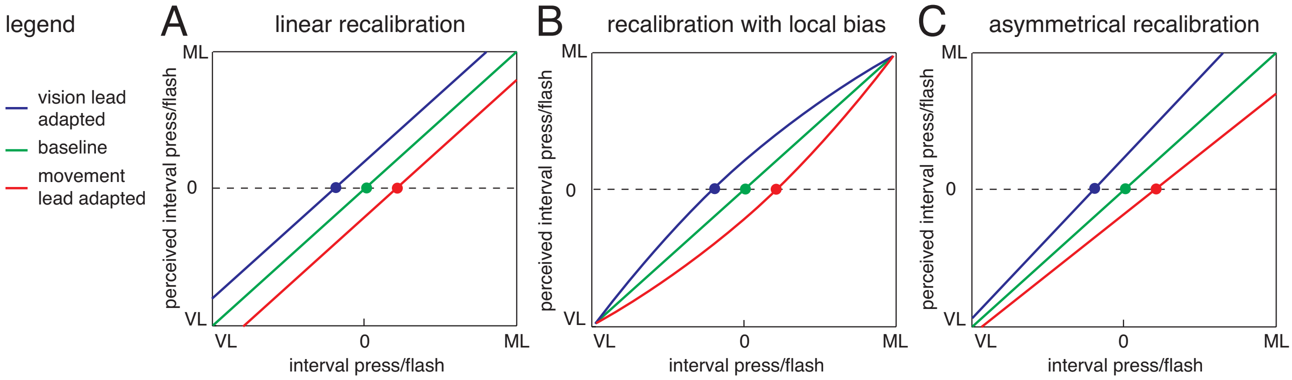


Figure 1: Examples of possible mappings of physical intervals (x-axis) to perceived intervals (y-axis) after adaptation to vision-lead (blue), baseline (green) and movement-lead (red) discrepancies.

2. Method and Materials

2.1. Set-Up

We used the same set-up as in earlier work (Rohde & Ernst, 2013). In a dark room participants placed their head on a chin-rest. During the experiment, subjects looked down in the direction of their hands, which were occluded from vision by a mirror (see Fig. 2). Participants's right index fingers were attached to a PHANToM force-feedback device with an elastic band. The right lower arm rested on a board. The device was programmed to simulate a virtual button (mass m=0.1 kg) with a throw of 8 mm, containing a 4 mm spring (spring constant k=500 kg/s2) and a dead-band of 4 mm (see Fig. 2A). After full compression, the button was pressed back up with a small restoring force (0.3 N; see Fig 2 B and C). Participants did not receive visual feedback about the position or compression of the button.

For the prediction of the timing of full compression of the button from early movement onset, the vertical displacement of the participant's finger during the button press was tracked in real time. An adaptive threshold predictor method (Rohde & Ernst, 2013) was used to predict the time of button press online from early movement onset. This prediction could be used to display visual stimuli even before a button press occurred. For very large target vision-lead SOAs (vision leads by more than 250 ms) this method becomes unreliable and the timing of the button press is predicted instead from the average press rate. For the entire range of vision-lead SOAs, the prediction contains some prediction error. To ensure a uniform distribution of SOAs, an algorithm dynamically rearranged target SOAs in case of such prediction errors (cf. Rohde & Ernst, 2013). For adaptation trials, the IQR of prediction error across subjects and conditions was 50±28 ms (median and IQR). This prediction noise, which is inevitable in the vision-lead condition, was mirrored (trial by trial) to the movement-lead condition, in order to assure that recalibration conditions remain comparable. In the baseline condition, the visual signal was always timed right after the button press.

A CRT monitor was mounted upside-down above the mirror. The mirror was used to project the visual probe stimuli into participants' field of view (white disks of 1.5° visual angle on a 50% gray background). The visual probe was projected at a fixed location in the area where participants pressed the button but was not spatially aligned with the fingertip. Stimuli were flashed for one frame (90 Hz refresh rate of monitor). The inherent endpoint-to-endpoint system latency between a button press and a corresponding flash on the screen is 34.5±7ms. Stimulus onset asynchronies (SOAs) given here in the paper do not yet subtract this inherent latency. That is, a baseline visuomotor lag of 0 corresponds to a scenario where a button triggers a visual stimulus that then flashes on the screen 34.5 ms later.

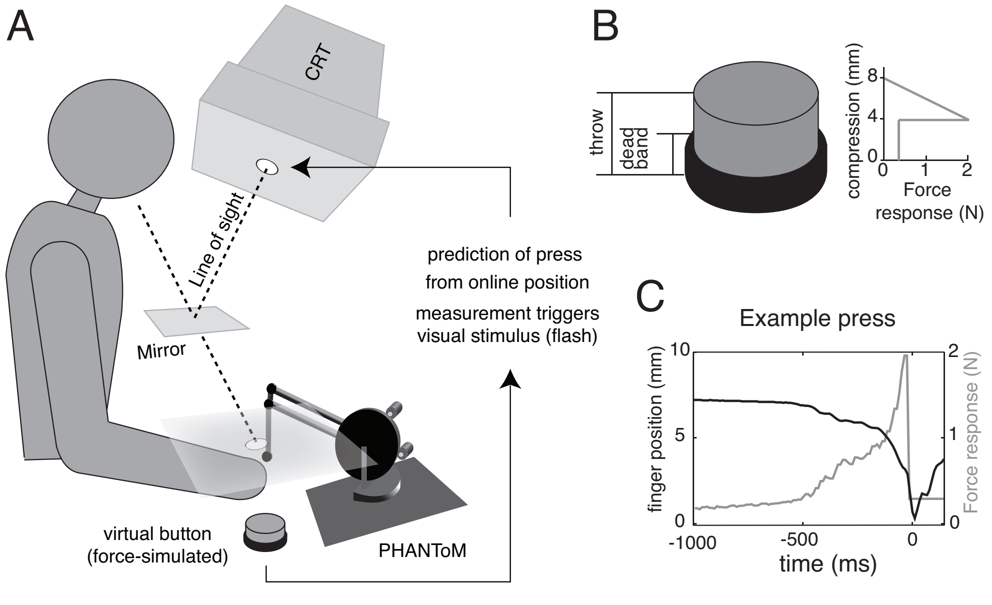


Figure 2: Illustration of the experimental set-up. A: The experimental set-up. B: The force response of the haptically displayed simulated button. C: Digit height (black) and force response (grey) in an example press.

2.2. Procedure and Task

6 participants (2 of the authors, 2 other lab members, 2 paid volunteers; 4 female, age range 20-32; all right-handed as by self-report) were tested in seven sessions on seven different days (overall ca. 10 h of experimentation per subject). The experiments were approved by the Ethics Committee of the University Clinics Tübingen, Germany. The procedure is in large parts adapted from an analogous study audiovisual recalibration (Roach et al., 2011). Visual stimuli were generated using the psychophysics toolbox (Kleiner et al., 2007).

In the first session (cf. Fig. 3 C), participants were habituated to the task. Firstly, in order to learn how the scale maps to intervals, they were presented with two visual stimuli. A red and a green dot (vertically displaced) were flashed after one another with SOAs uniformly distributed in [-300, 300] ms for 60 trials. After each trial, participants had to adjust the position of a black dot on a scale (Fig. 3 B) to indicate the perceived SOA, using the left and right cursor keys on a keyboard with the index and middle finger of the left hand. Participants submitted their response using the space key and were given feedback afterwards (blue dot at “correct” location on the scale). The initial position of the dot on the scale was random. The range of the scale corresponds to the interval [-300, 300] ms, the same range from which the SOAs were drawn. The width on the screen was 33° visual angle. The dot velocity was 270 ms (on the scale) per second (steps of 3 ms read in at 90 Hz). The scale had no labels but had vertical bars at intervals corresponding to 50 ms (see Fig. 3, B). This implies that the centre of the scale is clearly visually marked, as in Roach et al.‘s (2011) study.

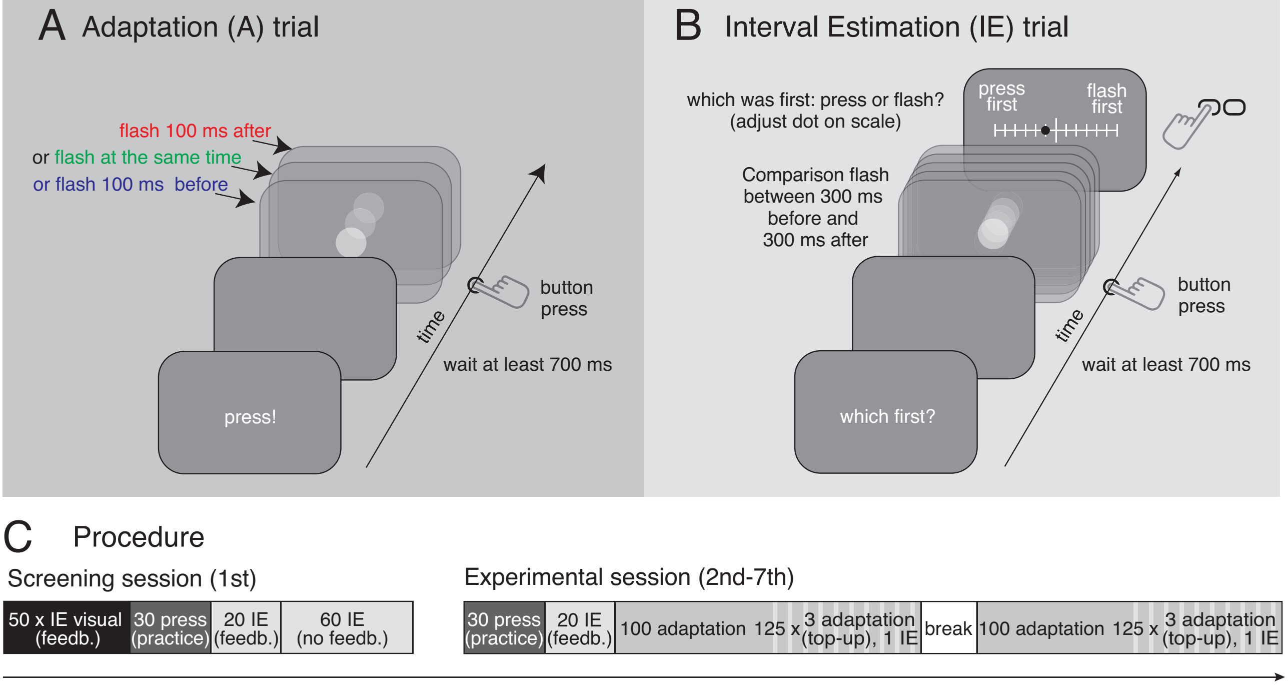


Figure 3: Illustration of procedure and task. A: Adaptation trials B: Interval Estimation trials. C: Timeline of the procedure in different blocks.

After this practice with visual stimuli only, participants pressed the virtual button for 30 times to initiate the prediction algorithm for VL discrepancies (cf. Appendix A). Throughout the experiment, participants were instructed to wait for at least 700 ms and as long as they wanted after a trial started before pressing the button to avoid that the signal that starts a trial has an influence on time perception. If participants pressed the button too early, trials were repeated (7% of all trials for all subjects in the experiment). Participants then performed 20 visuomotor IE trials (Fig. 3, B) with feedback, during which they were only presented with SOAs from the extreme ends of the scale

(|*lag*| > *200 ms*). They were instructed to estimate the interval between the full compression of the button and the flashed dot, using the same adjustment method described above for the visual-visual practice. Afterwards they performed 60 IE trials without feedback where SOAs were uniformly drawn from the full range of SOAs ([-300, 300] ms). This corresponds to the experimental task in later blocks. If participants missed a trial, they could indicate this and the trial was repeated at a later stage during the experiment (1% of all trials for all subject in the experiment).

In the six following sessions, participants were trained with one of the three training lags (VL: -100 ms, B: 0 ms, ML: 100 ms) for two subsequent experimental sessions, where each session consisted of two blocks (Fig. 3 C). The order of these conditions was counter-balanced across participants. An experimental session started with 30 button presses to initiate the predictor. Then, participants performed 20 IE trials with large SOAs (|*lag*| > *200 ms*) with feedback to remind them of the temporal interpretation of the scale. Afterwards, participants performed two identical blocks where they were first exposed to 100 adaptation trials (Fig 3 A) during which they only saw a flash timed relative to their button press. Then they performed the IE task for 125 trials where SOAs were drawn uniformly from the interval [300, -300] ms, with 3 top-up adaptation trials in between IE trials. This means that there were 500 responses to the IE task for each subject and condition at the end of the experiment. No feedback was provided.

2.3. Analysis

As in the study by Roach et al. (2011), results were pooled across participants, given that results from individual participants are too sparse for individual analysis.

The results were pre-processed to filter outliers due to errors in the measurement technique. Trials where the timing between the press and the flash was larger 500 ms were discarded. Also, trials where the adjusted value was within 12 ms of either end of the scale were discarded because it is not clear if participants perceived them to be at that location or even further outside the scale. In the later experimental blocks, a regression line was fit using the Matlab function *robustfit* (Statistics toolbox - iteratively reweighted least square). This very coarse approximation served to detect clear outliers in the adjustment. Outliers were discarded if the re-weighting assigned them a weight smaller than 0.2. Taking these three filters together, 7% of trials were thus discarded, leaving on average 2740 data points pooled across subjects per condition.

To test for differences between the conditions along the range of SOAs, IE responses were binned in 25 ms bins and 95% confidence intervals were computed using non-parametric bootstrapping (Matlab function bootci, 1000 iterations). The IE judgments were also interpreted as ternary (flash first, simultaneous, press first) temporal order decisions (cf. Allan, 975; Ulrich, 1987; Yarrow et al., 2011) to be able to compare the results with those obtained in other studies. IE responses with an absolute value larger than 12 ms were rated as temporal order judgments, i.e., either vision-first, or movement-first. IE responses with an absolute value smaller or equal to 12 ms were rated as simultaneous responses. Within this interval, the dot to be adjusted (cf. Fig. 3 B) overlapped with the vertical bar indicating simultaneity. Some subjects reported that they used this criterion to indicate perceived simultaneity (a more exact placement of the dot was difficult given the speed of the dot in response to the key press).

A psychometric function in form of a cumulative Gaussian was fit to the TOJ responses generated from the IE settings to derive the PSS and the just noticeable difference (JND). PSS and JND were the only free parameters. This was done using the Matlab toolbox psignifit (Wichmann & Hill, 2001a, 2001b). Another psychometric function (two-criterion model; cf. Cravo et al., 2011; Yarrow et al., 2011) was fitted to the SJ responses (least mean square fit). With this approach, the bell-shaped probability distribution obtained with SJ tasks is modeled as the difference between two cumulative Gaussian functions. The centres (μ_V and μ_M) of the flanking Gaussians mark the corners of a window of perceived simultaneity. The model was fitted with three free parameters (the midpoints μ_V and μ_M and the variance σ of the two cumulative Gaussians). Confidence intervals were computed using non-parametric bootstrapping.

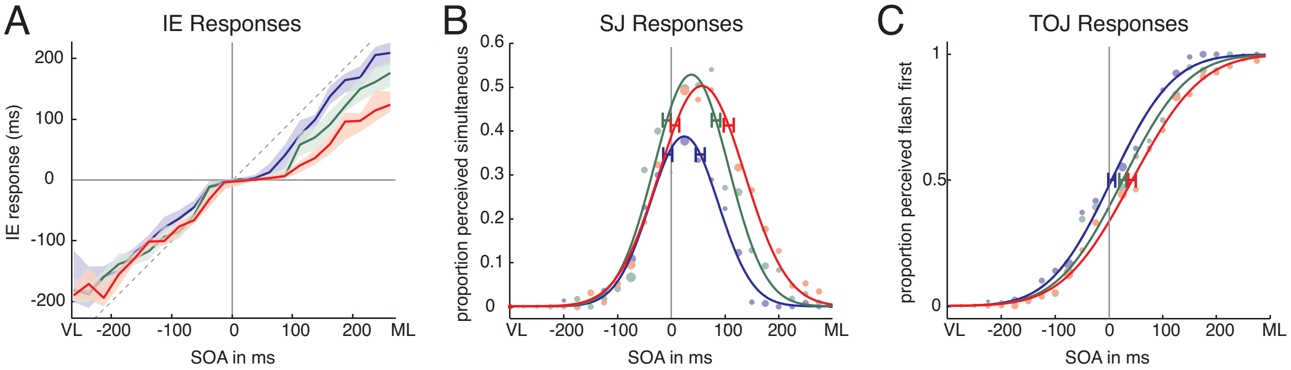


Figure 4: Perceptual responses after adapting to vision-lead (blue), baseline (green) or movement-lead (red) discrepancies. A: IE responses. Median and confidence intervals (25 ms bins) for all conditions. B: SJ responses. Psychometric curves and perceptual responses (binned for visualization). Bootstrap confidence intervals of μ_V and μ_M in plots. C: TOJ responses. Psychometric curves and responses (binned for visualization). Bootstrap confidence intervals on the estimated PSS.

3. Results

3.1 Interval Estimation

All subjects were able to perform the task. The IE responses at the end of the practice session significantly correlated with the SOAs presented (all Pearson's $r \geq 0.79$ and all $p \ll 0.001$). As common for magnitude estimation tasks, there was a centering bias in the responses (Poulton, 1979). The slope of regression lines fitted varied between 0.56 and 0.81. Important for our study, however, is the difference between the three different training conditions.

As in Roach et al.'s (2011) study, there is an 'S'-shaped compressive bias at the centre of the scale, where participants perceive close to simultaneity over an extended range of SOAs (Fig. 4 A). Concerning the comparison between the three conditions, the only significant differences are on the ML side of the range of SOAs (right in Fig 4 A). There, the distribution of IE responses shifts in the predicted order (VL top, B middle, ML bottom) and in a fashion that is roughly consistent with an explanation of a general shift in perceived intervals (cf. Fig 1A). For ML SOAs > 150 ms, the differences between conditions are ca. 40% of the difference in trained discrepancy between conditions. However, there are no significant differences between the three conditions on the VL side of the range of SOAs. A striking asymmetry in recalibration is revealed. This discontinuity appears to be due to an expansion and contraction of the range of SOAs that are perceived as simultaneous. The 'S'-shaped compressive bias extends more or less into the ML range of SOAs as a result of recalibration. The larger the training discrepancy, the more stimuli are perceived as simultaneous.

3.2 Simultaneity Judgments

The results from the SJ reinterpretation of the IE responses (Fig. 4 B) confirm this observation. The window of perceived simultaneity grows and shrinks on the ML side of the range of SOAs following the trained discrepancy. The two-criterion approach (Cravo et al., 2011; Yarrow et al., 2011) assumes that an SJ involves two perceptual decisions: Whether the sensed flash is before the

μ_V criterion and whether it is after the μ_M criterion (cf. Fig. 5 B). The combination of these two decisions is modeled as the difference between two cumulative Gaussian functions, resulting in a bell-shaped response distribution. The μ_V criterion hardly changes between conditions: (VL: $\mu_V = -7$ ms; B: $\mu_V = -8$ ms; ML: $\mu_V = 7$ ms; no significant differences), whereas the μ_M criterion shifts substantially in the predicted direction (VL: $\mu_M = 55$ ms; B: $\mu_M = 83$ ms; ML: $\mu_M = 107$ ms; all conditions different at $p<0.05$). There are no significant differences in estimates of the slopes (all σ estimates in [61, 73] ms)

3.3 Temporal Order Judgments

The PSS estimates that result from the TOJ reinterpretation of the IE responses vary in the predicted fashion between conditions. Recalibration to VL discrepancies moves the PSS to the VL side of the range. ML adaptation moves PSS away from it (see Fig. 4 C). There are no sizeable differences in magnitude of these shifts (estimates and confidence intervals in ms: VL PSS = 5, CI = [-1, 12]; B PSS = 26, CI = [20, 33]; ML PSS = 44, CI = [37, 50]). PSS was shifted approximately 20% of the trained discrepancy in both directions. This is consistent with our earlier results (Rohde & Ernst, 2013), where participants shifted 20-25% of the trained discrepancy but less than in other studies, where PSS-shifts of the order of 30-44% are reported for visuomotor delay adaptation (Stetson et al., 2006; Heron et al., 2009; Sugano et al., 2010).

The asymmetrical recalibration of IE is thus not accompanied by an asymmetrical recalibration of PSS. There were also no significant differences in JND between conditions (all JNDs in [90, 101] ms), which is a surprising result; at least intuitively, one would expect a decrease in perceptual precision given a larger window of perceived simultaneity. This is theoretically and empirically not the case (cf. Sect. 4.3).

4. Discussion

The observed pattern of recalibration does not correspond to either of the options given in Fig. 1. It involves a uni-lateral contraction or expansion of the area in which SOAs are perceived as simultaneous. While the responses on the VL side of the range of SOAs barely change, changes on the ML side of the range are substantial.

4.1 Visuomotor vs. visuo-auditory temporal recalibration.

When is temporal recalibration asymmetrical? The mechanisms of multisensory temporal recalibration tend to work symmetrically, if both sensory events are passively sensed (e.g., Fujisaki et al., 2004; Keetels & Vroomen, 2008; Di Luca et al., 2009; Roach et al., 2011; Yarrow et al., 2011). Cai et al. (2012) propose a model that also predicts symmetry in the visuomotor case, despite the asymmetry in the underlying cause-effect structure. Our previous work using a TOJ paradigm appeared to support this proposal, as visuomotor PSS were shifted symmetrically due to temporal recalibration. This led us to conclude that the mechanisms of visuomotor recalibration may well work symmetrically (Rohde & Ernst, 2013).

The current results subsume and reproduce our earlier result (TOJ reinterpretation of the results shows symmetrical PSS-shifts and no changes in JND). However, the analysis of the IE and SJ responses reveal a pattern that leads us to the opposite conclusion, i.e., that visuomotor delay adaptation is strongly asymmetrical around the point of physical simultaneity. This asymmetry sets visuomotor temporal recalibration apart from recalibration in other modalties. Audiovisual recalibration of IE may not be linear (Roach et al., 2011), but this non-linearity is symmetrical around simultaneity. Audiovisual recalibration of SJ may involve uni-directional expansions of the window of perceived simultaneity (Yarrow et al., 2011), but this is immaterial of whether the visual or the auditory stimuli leads the temporal order. The observed asymmetries appear to be specific to the visuomotor, or possibly the sensorimotor scenario.

Previous research is in partial agreement with the current results. Keetels and Vroomen (2012) report a widening of the window of simultaneity in a visuomotor recalibration experiment using SJs, but also a shift of this window. While this result supports our conclusion that ML recalibration is biased towards a shift of the μ_M criterion, it also suggests a small shift of the μ_V criterion. In a similar paradigm, Heron et al. (2009) only report the midpoint of the distribution (PSS), but graphical depiction of results from an example participant suggest a result similar to that reported by Keetels & Vroomen (2012). However, both Heron et al. (2009) and Keetels & Vroomen (2012) measure SJ responses at only five SOAs from the ML-side and use a Gaussian function to approximate the responses. While this is sufficient for estimation of PSS, it does not give a good impression of the shape of the response profile. Only rigorous future research will clarify how strong the directional specificity of visuomotor temporal recalibration really is.

The asymmetrical recalibration we observe appears to be a hallmark of visuomotor temporal processing and sets it apart from other forms of temporal recalibration that involve the sensation of external sensory events only.

4.2 Visuomotor temporal recalibration and intentional binding

What causes this asymmetry? If a person believes that she is the causal origin of a sensory event, this has been shown to induce a compression of the perceived interval between the triggering action and the resulting sensory event (intentional or causal binding, e.g., Haggard et al., 2002; Eagleman & Holcombe, 2002; Buehner & Humphreys, 2009). Humphreys & Buehner (2009) have demonstrated that this temporal compression due to intentional binding also occurs in an IE task. Can intentional binding explain the asymmetry?

It is likely that intentional binding plays into the *unity assumption* (Welch & Warren, 1980), i.e., the belief that two sensory cues belong together, which is a prerequisite for multisensory integration. The temporal compression observed under intentional (or causal) binding could then be explained as an instance of the more general phenomenon of multisensory integration, which involves the merging of cues from different modalities into a single percept (Ernst & Bülthoff, 2004). This occurs only within a small temporal window around simultaneity, often called the temporal window of integration (Shams et al., 2002; Bresciani et al., 2005). The ‘S’-shaped compressive bias around simultaneity could well be a consequence of this window of temporal integration. If intentional binding affects visuomotor temporal integration, this could explain the asymmetries in visuomotor temporal recalibration as integration phenomena should be more pronounced for movement-lead stimuli in the first place. This possibility predicts similar asymmetries in recalibration of other kinds of sensorimotor time perception (e.g., in auditory-motor or tactile-motor recalibration). Also, if intentional binding and temporal recalibration are part of the same basic perceptual integration process, a manipulation of intentional binding (e.g., active vs. passive or voluntary vs. involuntary movement) should modulate shifts in perceived timing due to recalibration. Empirical research can test these predictions. Given that intentional binding itself relies on several factors (Moore et al., 2009), it will, however, be difficult to generate exact quantitative predictions.

It is impossible to draw conclusions on this matter as we did not measure or manipulate intentional binding. Yet, intentional binding related processes seem to offer the only convincing explanation for the results.

4.3 Models of time perception and the window of integration

How do the different measures of simultaneity SJ, IE, and TOJ relate? The IE and SJ results demonstrate the existence of a marked asymmetry in visuomotor recalibration. It is somewhat surprising that no traces of this asymmetry can be detected by the TOJ reinterpretation of the same result. To discuss different kinds of temporal judgments and what to expect of different parameter estimates, it is helpful to recall the assumptions underlying the fitting of different kinds of psychometric curves.

Figure 5 A depicts the most general and straightforward model of time perception – a process of SOA measurement with Gaussian noise, depicted as the blurred identity line. In this model, IE judgments would be expected to reproduce the blurred diagonal itself, an intuition that is captured in the linear recalibration hypothesis (Fig. 1 A; also Roach et al., 2011). A TOJ involves the perceptual decision, whether a stimulus is before or after simultaneity, which results from integrating the probability that a SOA is sensed above or below the criterion (simultaneity). This yields a cumulative Gaussian function. The probability distribution of SJ responses is often not quite correctly modeled as a Gaussian probability distribution (cf. Vroomen & Keetels, 2010; Yarrow et al., 2011), which roughly corresponds to a cross section through this blurred diagonal. In this model, the width of the window of simultaneity represents the amount of estimation noise, i.e., the amount by which the diagonal is blurred. Therefore, a widening of the window of simultaneity would be accompanied by a marked decrease in discriminability (JND) in TOJs.

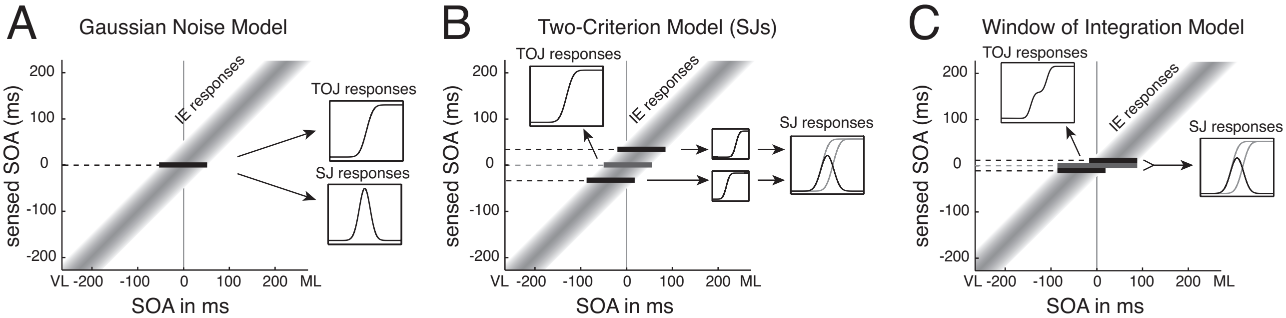


Figure 5: Illustration of different models of time perception. A: Simple Gaussian noise model. B: Two-criterion model for SJs. C: Window of integration Model. Figure adapted from Yarrow et al., (2011).

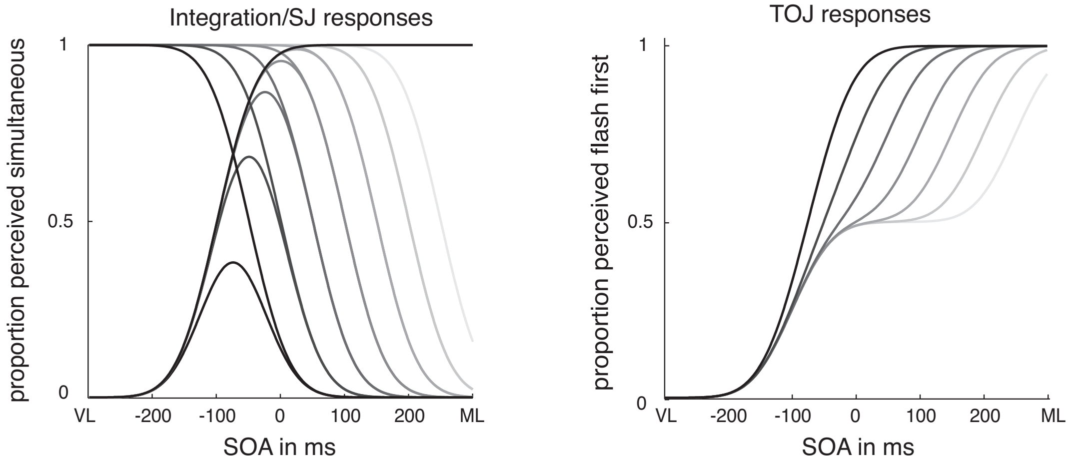
Cravo et al. (2011) and Yarrow et al. (2011) recently proposed that SJs should instead be modeled as a two-criterion decision process. Yarrow et al. (2011) correctly point out that it is not clear by which process the cross-section approach (Fig. 5 A) should be realized. Indeed, the probability for registering an SOA as having an exact size (e.g., simultaneity) is infinitesimal. They propose to model SJs as a two-criterion decision (cf. Fig. 5 B). A window of simultaneity is defined (here: criteria μ_V and μ_M). The probability of perceiving simultaneity then is the probability of a registered SOA falling between these two criteria, i.e., the difference between the two cumulative Gaussian functions flanking this window (Fig 5 B). Yarrow et al. (2011) gave evidence in favour of this model by showing that recalibration of audiovisual SJs is better modeled as a uni-lateral criterion shift. TOJ responses are then modeled as a perceptual decision as in the Gaussian noise model (Fig. 5 A) with respect to another criterion that could be placed anywhere inside the window of simultaneity (Fig 5 B; cf. Yarrow et al., 2011).

While this is a plausible model, it is difficult to reconcile with the existence of a plateau at simultaneity in IE responses (Section 3; Roach et al., 2011). Of course it is possible that this plateau is an artifact of the IE procedure (response bias). However, both our and the Roach et al.'s (2011) study reproduce the PSS shifts typically found in TOJ paradigms from the IE responses. This means that, at least theoretically, the IE procedure may capture the distribution underlying recalibration of

TOJs. Also, it has been shown that multisensory integration usually involves the loss of access to the uni-sensory estimates (Ernst & Bülthoff, 2004). It seems possible and plausible that this would lead to a compressive bias around simultaneity in the registration of SOAs already.

We therefore want to discuss a third possibility, where temporal integration occurs prior to registration of an SOA (Fig. 5 C). We illustrate this with a model where integration is implemented as a two-criterion process as the one proposed for SJs by Cravo et al. (2011) and Yarrow et al. (2011). This leads to a discontinuity in the registered SOAs (offset in blurred line), which is reflected in a 'S'-shaped compressive bias at simultaneity in the IE responses. Crucially, in this model, TOJs do not follow a cumulative Gaussian distribution. Instead, they follow the distorted distribution depicted in Fig. 6 A (left): As the window of integration widens, a more and more marked plateau is inserted at the PSS.

A Two-Criterion Model of integration



B Model behaviour and experimental results

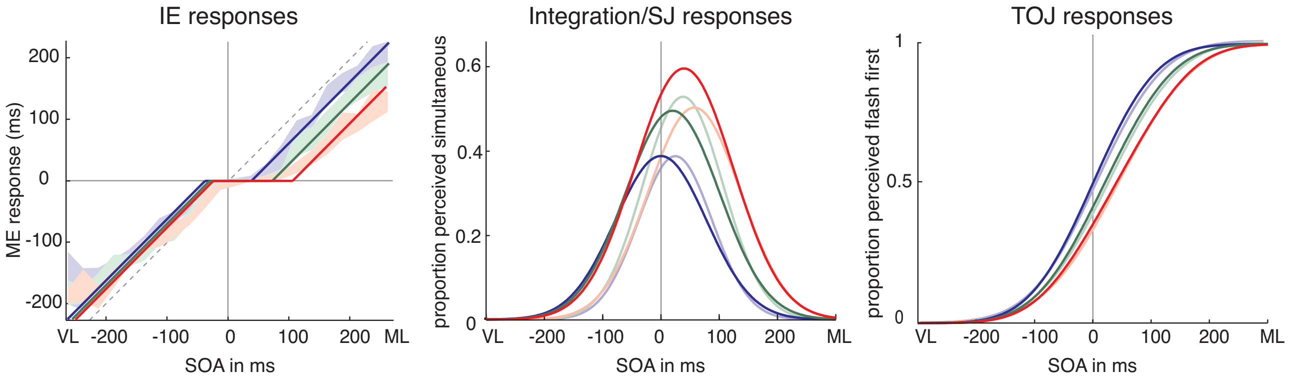


Figure 6: Behaviour of the two criterion-model of integration for different placement of criteria. A: The expected SJ responses (left) and TOJ responses (right) for different criteria placements demonstrate the behavior of the model for extreme values. μ_V: always -100 ms. μ_M (from black to light grey): -50, -0, 50, 100, 150, 200, 250 ms. All σ=50 ms. B: Model behavior (dark lines) for an example parameter set of the model and empirical results (pale). μ_V = -37, -29, -24 ms; μ_M = 37, 69, 104; σ = 75ms. The locations of μ_V and μ_M are computed from the IE results by fitting an identity line with a plateau (least mean square).

Figure 6 B depicts how the model behaves for a parameter set that is similar to the experimental results (Fig. 4). Important is that the probability distributions for TOJ responses in this example are virtually indistinguishable from cumulative Gaussians with a shift in PSS. Even though there are small differences in slope, too, these would be very difficult to detect given the amount of noise usually present in this kind of task[1]. If this kind of integration is happening even prior to judgments about temporal order, our measurements will probably not be sensitive enough to detect the deviations of our judgments from the cumulative Gaussian profile.

This example is not meant as an actual generative or descriptive model of our results. Such a model would be impossible, given that, for instance, the SJ and TOJ interpretation of the result do not exactly correspond in their estimate of PSS. Such a model would also be of limited explanatory power, given that SJ and TOJ responses were generated using the very IE responses, so it is not surprising that there is a link. Also, a biologically plausible model of the window of integration would probably involve a softer compressive bias than discontinuously cutting out a chunk of registered SOAs. The point of this model is to call into question the assumption that time perception generally and TOJs specifically rely on a simple registration process with Gaussian noise (Fig. 5 A) and to demonstrate that, if there were a window of integration as in Fig 5 C, it would be very difficult to detect using TOJ approaches.

A similar argument can be made about simultaneity judgments. Unless there were extreme distortions of the underlying distribution, it would be impossible to disambiguate between widely placed criteria on a distribution with Gaussian noise (Fig. 5 B) and very tightly placed criteria (Fig. 5 C) on a distribution that already has undergone integration. Importantly, this also implies that a criterion shift detected using a two-criterion model (results presented here; Yarrow et al., 2011) could either represent a true shift in criterion or a modulation of the underlying window of temporal integration.

Given the similarity of the respective distributions, for all practical purposes, fitting a cumulative Gaussian function to TOJ results will yield good estimates of perceptual bias (PSS) and precision (JND), and fitting a two-criterion model to SJ results will yield good estimates of the width and location of the window of simultaneity. However, the field of time perception gradually shifts its attention to possible neural implementations of SJs, TOJs and IEs (e.g., Roach et al., 2011; Cai et al, 2012). Therefore, it is important to consider the possibility of perceptual integration and a consequent distortion of temporal registration at an early stage of processing, even if our most common formal tools to describe human time perception fail to register this.

4.4 Limitations of the results

Are the results conclusive? There are weaknesses in the experimental paradigm. Firstly, magnitude estimation tasks are generally prone to cognitive bias (Poulton, 1979). In particular, the existence of a clearly demarcated point of simultaneity on the scale could exaggerate the density of responses at perceived simultaneity. Secondly, it is not clear in how far the interpretation of the IE responses as ternary TOJs (vision first, simultaneous, movement first) is comparable to results from SJ or TOJ paradigms. Thirdly, the results presented may include distortions, as results were pooled across participants that may well have differed in biases or perceptual precision, and the statistical power is comparably low on both the individual and the population level. However, none of these shortcomings can explain the existence of the reported asymmetry in the results. This asymmetry poses a challenge for models of recalibration that are not sensitive to whether vision or movement leads the temporal order (e.g., Cai et al., 2012).

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[1] In linking the IE results to the TOJ re-interpretation it is important to recall that in Fig. 6 A and 4A, the shaded area depicts the confidence interval of the median in that bin, not the spread of the results, which is considerable, even around the ‘S’-shaped compressive bias.

5. Conclusion

The results presented show an asymmetry in the temporal recalibration of visuomotor interval perception that is intriguing in a number of ways (1) It points out a qualitative difference between visuomotor and visuo-auditory recalibration (asymmetry) that was thus far unknown. (2) It suggests a link between visuomotor temporal recalibration and intentional binding. (3) The comparison with our earlier results (Rohde & Ernst, 2013) raises more general questions about how different types of perceptual judgments in time perception (SJ, TOJ, IE) relate and how they are influenced by a temporal integration. Further research is required to gain clarity about all these three points. Yet, the possibility that the window of temporal integration, intentional binding and the recalibration of perceived simultaneity could all be aspects of the same process of visuomotor integration should be taken seriously and deserves further attention.

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