Exposure-induced temporal recalibration in audio-visual events: Investigating the role of decisional and sensory processes involved in timing judgments

Despite being one of the fundamental dimensions of experience, the question of how do we assess simultaneity in multisensory events, especially when there is difference in both transmission and transgression time for the sound and light, remains poorly understood. Recent findings have demonstrated an existence of an elastic time model in which recent history of relative timing can modify the perception of relative time. However, mechanisms underlying the changes are not entirely clear. Here, in the first experiment we show that estimates regarding the temporal relationship between audio and visual signals involve decisional processes operating on the outcome of timing processes. In the second experiment we seek to investigate the relationship between absolute time encoding and relative time encoding for audiovisual events and find that mechanisms underlying exposure-induced changes are similar for both kinds of processing. Considering these findings, present study demonstrates that exposure-induced changes in relative timing judgments of audiovisual stimuli depend not only on the sensory representation of the temporal relationship, but also on decisional factors, judgment strategies, and/or any response biases adopted by observers.

1. Introduction

Our perception of the world is not often contaminated with mismatches or illusory scenes. We typically perceive external events as coherent and intact multisensory entities. When a cup falls to the ground in front of us, for example, we see and hear it happen simultaneously. Determining the temporal relationship of multisensory signals, therefore, might be an important perceptual operation to categorize events that are tied together -thus should be integrated into a single percept and independent of others. Given this significance, the current gap in our understanding of how does the brain represents time is surprising.

Most of the physical events happening around us generate audio and visual signals, however, due to the physical factors inherited in these signals, assessing the simultaneity from an audiovisual event can be a challenge for the nervous system. Firstly, light and sound have differential velocities in the air, therefore, the physical arrival time of sound signal changes with distance from the event (Heron et al, 2007; Heron et al, 2012b; King & Palmer, 1985; Regan, 1989). In other words, for distant events the light has a 'head start' over sound because of the faster travelling speed of light waves (e.g. we see the lighting before hearing the clash). More interestingly, even when the sound and the light signals hit the sensory organs at the same time, depending on the intensity, neural transduction auditory information is faster (~30ms) than visual information (Alais & Carlisle, 2005; Heron et al, 2007, Heron et al, 2012a; Regan et al, 1989). Therefore, the nervous system possesses a degree of temporal elasticity, which allows it to dynamically recalibrate signals in different modalities to maintain a veridical percept of the world. The mechanism underlying this *colligated* simultaneity in multisensory events may have fundamental implications for understanding how the brain represents time.

In line with this proposed elastic time model, in the last decade, studies demonstrated that our perception of multi-sensory relative timing is influenced by a recent history of relative timing stimulation (see Linares et al, 2016 for a review). In Fujisaki et al's seminal report, for example, it was shown that after repeatedly presented with a fixed asynchrony between audio and visual signals (e.g. sound following visual by 400ms), observers' point of subjective simultaneity (PSS) shifts towards the adapted value, thus they appear to perceive small asynchronies as occurring closer in time (Fujisaki, 2004; Hanson et al, 2008; Heron et al, 2007; Keetels & Vroomen, 2008; Miyazaki et al, 2006; Roach et al, 2010; Roseboom et al, 2015; Vatakis et al, 2008; Vroomen et al, 2004; Yarrow et al, 2015; Yuan & Huang, 2015). It is as though, after having lived briefly in a world containing a constant audio or visual delay, people come to accept this timing relationship as synchronous.

'Lag adaptation effect' underlying the change in PSS appear analogous to the classical after-effects observed in visual adaptation studies. That is to say, after having exposed to a fixed value of the stimulus attribute, the subsequent attribute perceived as more *unlike* to the adapted sensory property, thus repelled away from the adapted value (Kohn, 2007; Webster, 2011). For example, prolonged exposure to high contrast vertical pattern reduces the perceived contrasts of the subsequent pattern in a way that the subsequent low contrast pattern perceived as having even lower contrast (Graham, 1989; Kohn, 2007). Identical pattern of results are commonly found in color perception (McCollough 1965; Webster, 2011), orientation (tilt after-effect, Gibson, 1937), motion direction studies (direction aftereffect; Addams, 1834; Alais & Blake, 1999; Clifford 2002; Levison & Sekuler, 1976). In addition to the repulsion effect, sensory adaptation appear to increase the discrimination ability around the adapted value for the subsequent percept (Kohn, 2007; Webster, 2011). Temporal analogue of the sensitivity changes following sensory adaptation was recently demonstrated (Roseboom et al, 2015). This further supported the idea that the mechanism of neural coding and sensory adaptation are similar for time and space (Heron et al, 2012a; Heron et al, 2012b; Linares et al, 2016; Roach et al, 2011; Roach et al, 2010; Roseboom et al, 2015).

Interestingly, exposure-induced perceptual aftereffects (sensory adaptation) appear to produce opposing behavioral effects to what Bayesian Integration Theory argues (Beck et al, 2008; Bulthoff, 1996; Knill & Pouget, 2004; Körding & Wolpert, 2004; Sato & Aihara, 2011; Yamamoto et al, 2012). When the uncertainty increases (like seeing in fog or mist), Bayesian

recalibration model asserts that the model should systematically increase its reliance on prior knowledge, as in past is a good predictor of present (Fischer & Whitney, 2014; Friston, 2009; Knill & Pouget, 2004; Körding & Wolpert, 2004). An optimal strategy that is defined by the Bayes rule[1] provides a framework for perception that can account for a large number of known perceptual aftereffects and illusions (Bernardo, 1994; Hillis et al, 2002; Hohwy, 2013; Knill & Pouget, 2004; Shams, 2010; Webster, 2011). Studies in sensorimotor learning (Körding & Wolpert, 2004, 2006), cue combination (Trommershauser, 2011), visual motion perception (Sekuler et al, 1997) demonstrated the way in which the central nervous employs Bayesian probabilistic models.

To further investigate the interplay between Bayesian recalibration and lag adaptation effect, Miyazaki et al revealed that when observers were exposed to asynchronously delivered somatosensory signals that were delivered on to each hand and later asked to judge the temporal order of the tactile stimulation, their reports showed the opposite perceptual changes that conform to a Bayesian integration theory (Miyazaki et al, 2006). In other words, after having exposed to left hand precedes the right hand by 400 ms, observers perceive all the subsequent values as more like 400ms –attracted towards the adapted value. To account for observed differential recalibration types in relative time judgments, they suggested that the lag adaptation may be peculiar to the audiovisual domain due to the long-term exposure to audiovisual asynchrony in nature, while somatosensory signals appear to operate in Bayesian terms (Miyazaki et al, 2006; Sato & Aihara, 2011; Yamamoto et al 2012). However, further investigations revealed that repeated exposure to asynchrony in audio-tactile (Hanson et al, 2008), and visuo-tactile (Hanson et al, 2008; Keetels & Vroomen, 2008; Takashi & Watanabe, 2008) also resulted in lag adaptation after-effect. Thereby, a single supramodal mechanism might be responsible for temporal recalibration of multisensory signals. In line with this idea, Yamamoto et al later proposed that Bayesian calibration is always at work for sensory signals of any modality and that the effect of Bayesian calibration is cancelled only when lag adaptation mechanisms operate in some particular combinations of sensory signals (see figure 1) (Yamamoto et al, 2012). Consisted with their proposal, they demonstrated an experimental design where Bayesian recalibration of simultaneity in audiovisual pairing can be observed (Yamamoto et al, 2012).

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[1] Humans internally represent both the statistical distribution of the task and their sensory uncertainty and combine them optimally (Friston, 2009; Knill & Pouget, 2004; Körding & Wolpert, 2004.
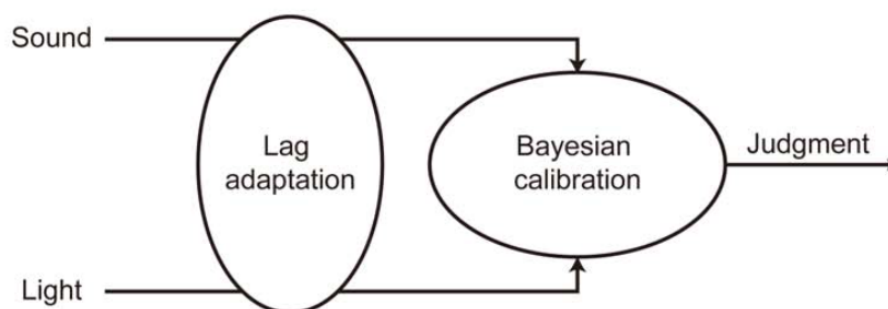
Figure 1: Illustration of Yamamoto's proposed mechanism for temporal aftereffects (Yamamoto et al, 2012).

At present, however, little is known about the nature of the mechanisms underlying this *temporal recalibration*. One explanation asserts that the time comparator dynamically coordinates the latencies of asynchronous auditory and visual input -like synchronizing two clocks- so that the delay is unnoticed (Di Luca et al, 2009; Navarra et al, 2009). Another proposal is suggesting that the change in perception after asynchrony exposure occur because asynchrony exposure reduces the reactiveness of population of neurons that are maximally responsive to a relatively narrow range of asynchronies, while the decoder was not aware of the adaptation (Becker & Rasmussen, 2007; Heron et al, 2012a; Ivry, 1996). Behavioral evidence for the existence of the population codes for asynchronies were recently demonstrated in human temporal judgments (Heron et al, 2012a), following a physiological evidence for orientation specific neurons in visual area V1 (Hubel, & Wiesel, 1968). An alternative proposal is suggesting that asynchrony exposure might change the frame of reference for categorizing events as simultaneous or not, without changing the sensory representation of the events (Yarrow et al, 2011, 2015). A recent attempt to investigate which above mentioned mechanisms best accounts for audiovisual temporal recalibration led to the finding that latency shift and criterion change models were arguably better at describing the observed pattern of results in audiovisual relative timing judgments (Yarrow et al, 2015).

Lag adaptation effect has been measured using simultaneity judgments (SJ) (Yarrow et al, 2015, 2011; Zampini et al, 2005), Temporal order judgments (TOJ) (Fujisaki, 2004; Vroomen et al, 2004), magnitude estimation task (Roach et al, 2010), multisensory integration (Fujisaki et al, 2004; Yuan & Huang, 2015; Sekuler et al, 1997), and more

recently, an objective three-alternative forced choice task (Roseboom et al, 2015). However, it is not entirely clear which mental processes underlie each behavioral task and identification of non-temporal components in those metrics of time is an active debate. For example, Elliot et al recently demonstrated that the perceptual reports for both simultaneity judgment and McGurk-task[2] do not coincide (Freeman, & Ipser, 2016). Similarly, a recent study suggested that perceptual latencies differ across SJ-task and TOJ-task (Linares & Holcombe, 2014). Contrary to this proposal, another study suggested that a common timing processes underlie SJ and TOJ tasks García-Pérez & Alcalá-Quintana, 2015). Be that as it may, the role of decisional processes on exposure-induced changes in subjective relative timing appear to determined by the particular experimental settings and design. Thereby, quantification of exposure-induced changes in perception poses a methodological challenge.

Present study attempts to develop a more sensitive test in order to dissociate the non-temporal factors (e.g. decisional processing) involved in simultaneity judgments. In particular, we wondered whether the range of adaptation distribution regimes (e.g. wide or narrow) would markedly influence observers' simultaneity judgments. We predicted that when adaptation values distributed from a wider range of values (like the world offers random asynchronies), observers would adopt a more liberal decision making on categorizing simultaneity, while sensory levels remain unaffected. Although this theoretical framework appears feasible, it awaits experimental validation. To this end, differently distributed adaptation sequences (e.g. synchrony and wide) with same mean value of 0 were individually tested and compared with magnitude estimation task involving the same stimuli and conditions. Such a result would provide an empirical demonstration that the threshold of simultaneity window derived from simultaneity judgments could depend on decisional factors (e.g. the range of SOAs adapted), thus it would bring into question the appropriate interpretation of the results of a number of previous simultaneity studies (Donohue et al, 2010; Yuan & Huang, 2015; Sekuler et al, 1997; Zampini et al, 2005).

From the above-mentioned review, one can conclude that how does the brain represent relative timing has not yet been satisfactorily resolved. Given the proposed role of Bayesian recalibration in processing temporal order of the relative time judgments (Yamamoto et al, 2012, Miyazaki et al, 2006), in experiment 2, I sought to investigate whether or not time is

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[2] Phoneme-identification task ('did you hear /ba/ or /da/'?), based on McGurk Illusion (McGurk & MacDonald, 1976).

encoded in absolute terms with a supramodel that encompasses timing of sensory inputs in absolute terms. I predicted to observe a clear, robust lag adaptation effect in relative timing reports following fixed asynchrony exposure (e.g. audio lead or vice versa), whereas we expect to see a globally operating lag adaptation effect for both sensory orders when observers asked to report absolute difference in relative asynchronies. To test these possibilities, we measured estimates in both relative magnitude estimation task and absolute magnitude estimation task to the presented audiovisual stimuli pairs with and without previous repeated exposure to fixed relative asynchrony.

2. Experiment 1

2.1. METHODS

(a) Participants

Six observers (4 male, 2 female, age: 21 –28 years) participated in the experiment. Observers included the author (G.E) and five further participants, all of which were naive as to the experimental purpose and reported normal or corrected to normal vision and hearing.

(b). Apparatus and materials

In a quiet, bright room, participants viewed stimuli from a distance of approximately 57 cm from the monitor. Visual stimuli were displayed on either Iiyama Vision Master Pro 203 or LaCie Electron 22 Blue II monitor, both with a resolution of 1024 x 768 pixels and refresh rate of 100 Hz. Audio signals were presented binaurally via Sennheiser HDA 280 PRO headphones. Generation and presentation of the stimuli were controlled by through Psychtoolbox 3 (Brainard, 1977; Pelli, 1997; Kleiner et al, 2007) run in MatLab (Mathworks, USA) on a Dell desktop PC. Participants responded using the mouse or keyboard.

Visual events were a luminance modulated Gaussian blob (standard deviation of the blob was 1.5 degrees of visual angle (dva). Relative peak luminance difference from background was Michelson contrast 1 (Michelson, 1927); displayed against a grey (approx. 38 cd /m^2) background (dva was used as an absolute measurement). A white (approx. 76 cd /m^2) fixation square (subtending 0.25 dva) was presented centrally with the blob appearing 3 dva above the

fixation square. The blob was presented for one frame approximating 10 ms in duration. Auditory signals were a 10 amplitude pulse of 1500 Hz sine-wave carrier at approximately 55 db SPL.

(c) Design

The experimental set consisted of 4 sessions, each lasting around 60 minutes. As depicted in Figure 2, in each session observers were presented with a light and sound separated by a random value selected from the nine intermediate stimulus-onset-asynchronies (SOAs)(±400, ±200, ±100, ± 50 and 0 ms), using the method of constant stimuli (Spence et al, 2001). Within the session, participants always completed an initial no-adaptation block, followed by the same number of trials of an exposure condition and followed by no-adaptation blocks at the end. Adaptation types consisted of two different types of distribution with the same mean value of 0. A 'synchronous adaptation' where stimulus pairs were presented with zero temporal difference, and a 'wide adaptation' where the temporal difference was distributed randomly from a range of SOA (-400 to 400). The order of completion of exposure conditions was counterbalanced across participants.

In keeping with previous work (Roseboom et al, 2015), adaptation sequences consisted of the presentation of five multisensory pairs with the exception of the long exposure sequence presented on the first and the middle trial of each block in which 60 multisensory pairs were presented. During the exposure sequences, observers were instructed to attend to the temporal order of the adapting stimuli but were not required to make perceptual judgments until presented with test stimuli. After the exposure top-up sequence, the fixation changed from white to black (approx. 0 cd /m^2) for 500 ms to alert participants that the subsequent pair was a test trial to which they needed to respond.

(d) Procedure

The experiment consisted of two unspeeded tasks, simultaneity judgment, and a magnitude estimation task. In simultaneity judgments, an observer indicated whether or not the sound and light came at the same time by pressing one of the two (yes or no) response keys. In Magnitude estimation task, they were asked to estimate the observed time interval between the onset time of audio and visual events by adjusting a visual slider presented on the screen

with the mouse. For each trial, the SOA indicator was randomized to avoid the effect of any potential biases related to the starting position. Negative SOAs indicated that the auditory signal was presented first, whereas positive values indicated that the visual signal was presented first. The order in which the two tasks were completed was counter-balanced across observers.

To facilitate a familiarity with the magnitude estimation task, practice was provided at the beginning of each day/session. The correlation between perceptual reports and physical SOA was acquired and only observers who obtained a correlation of 0.85 or above were permitted to proceed on the experimental blocks. Otherwise, they were asked to repeat the practice session until they reached the desired correlation between estimated SOA and physical SOA. The test sequence would then proceed as described for the no adaptation condition.

(e) Ethical Issues

The experiment complies fully with BPS guidelines (British Psychology Society, 2006) and ethical approval was obtained from the School of Psychology at the University of Sussex. Before taking part in the experiment, participants signed a consent form indicating that their participation was voluntary and that they could withdraw at anytime during the experiment. All the data were collected and analyzed anonymously (see appendix A).
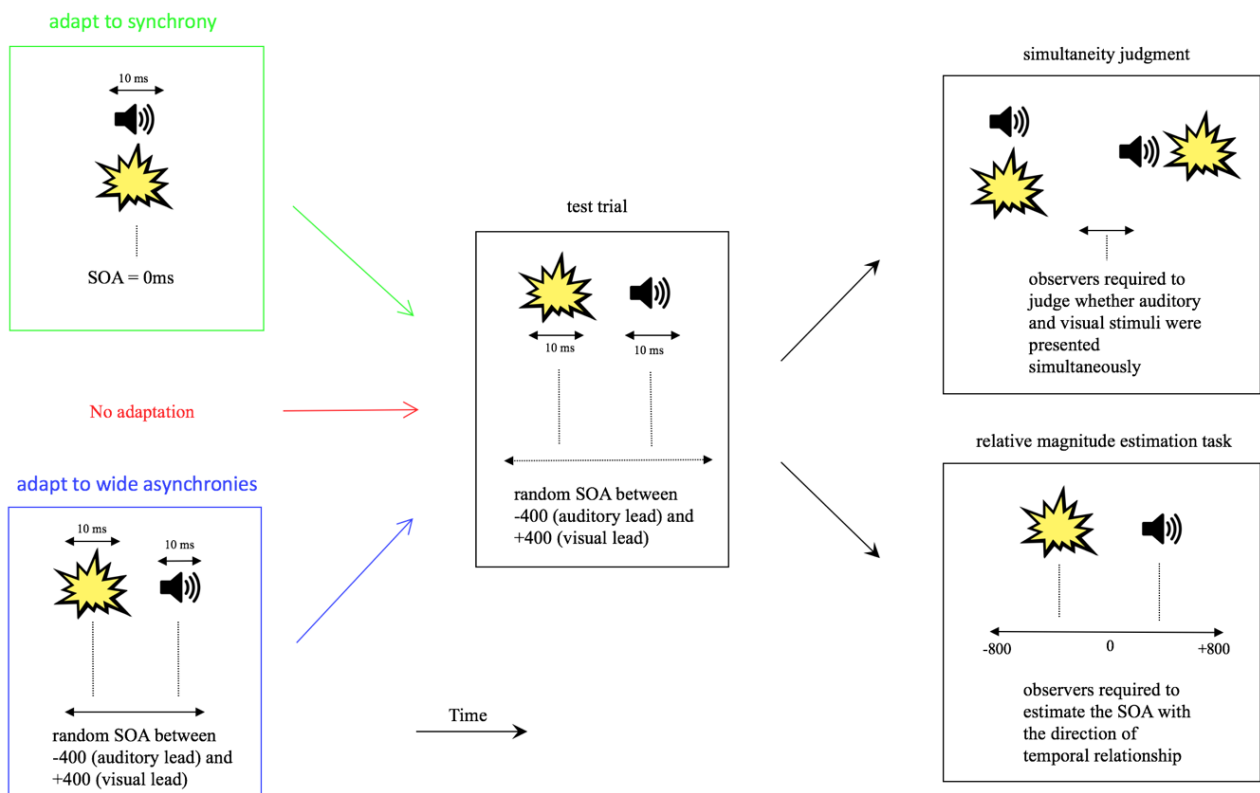
Figure 2: Schematic representation of the experimental sequence designed to investigate the dissociation between the metrics of time in response to different adaptation conditions. Prior to test trials, observers were exposed either to adaptation or not (depending on the session) and then made judgments about either simultaneity or SOA estimation separately. See the main text for details.

2.2. RESULTS

The present experiment sought to investigate the influence of non-temporal parameters in adaptation for simultaneity judgments. Conducted in separate analyses, responses to the temporal relationship between audio and visual were collected for both types of tasks. Changes in the criterion for categorizing simultaneity and precision in discriminating synchrony were individually investigated for the simultaneity judgment task following the adaptation.

Simultaneity Judgments

Judgments of asynchrony and synchrony were derived from each observer. Low criterion (corresponds the mean threshold for simultaneity judgments in audio leading visual asynchronies) and high criterion (corresponds the mean threshold for simultaneity judgments in visual leading asynchronies) and the standard deviation (SD) associated with each were estimated using Matlab (Mathworks, USA), by taking the difference of two cumulative Gaussians with SOA and variance of the difference between audio and visual onset time taken as parameters (Yarrow et al, 2011, 2013, 2015).

(a) Criterion changes for categorizing simultaneity

SOA values that relate to the boundary between judging that the two stimuli were simultaneous and not simultaneous were taken as a criterion for categorizing synchrony Modulation of subjective simultaneity window (defined as the area designated by the difference between synchrony criterions) were individually investigated in response to two different distribution regimes, while the no-adaptation condition was taken as a baseline. Inspection of raw proportion of synchrony responses, such as those in figure 3, suggests that following synchrony-adaptation, observers' criterion for synchrony was narrowed, thus they

appeared to have adopted a more conservative strategy in simultaneity judgments (M_{low} = 95.92 ms, SD_{low} = 48.74; M_{high} = 81.90 ms, SD_{high} = 32.04), compared to no-adaptation (M_{low} = 102.64 ms, SD_{low} = 55.63; M_{high} = 92.40, SD_{high} = 36.95). Opposite changes in criterion thresholds were observed following exposure to wide distribution (see figure 3a). Representative observer's proportion of synchrony responses are plotted in figure 3b.

To assess this possible effect of adaptation on simultaneity criteria, a 2 X 3 repeated-measures ANOVA for the absolute values of the synchrony criterions (high and low) and adaptation condition (no adapt, adapt to audio lead, adapt to visual lead) was conducted. Contrary to initial visual inspection, the results revealed no main effect of adaptation on criterion thresholds ($F_{(2,10)}$ = 1.21, p = .34, η^2 = 0.194), nor an interaction involving adaptation and criterion side factor ($F_{(2,10)}$ = 0.02, p = .97, η^2 = 0.005). This implies that the type of adaptation presented before the experiment trials had no effect on the simultaneity criterions. In a further analysis a Bayesian repeated measures ANOVA indicated only anecdotal evidence in favor of the null hypothesis (BF_{10} = 0.391, %$_{error}$ = 0.893) (JASP Team, 2016). This suggests that there was insufficient evidence to differentiate synchrony criteria in the different adaptation conditions.
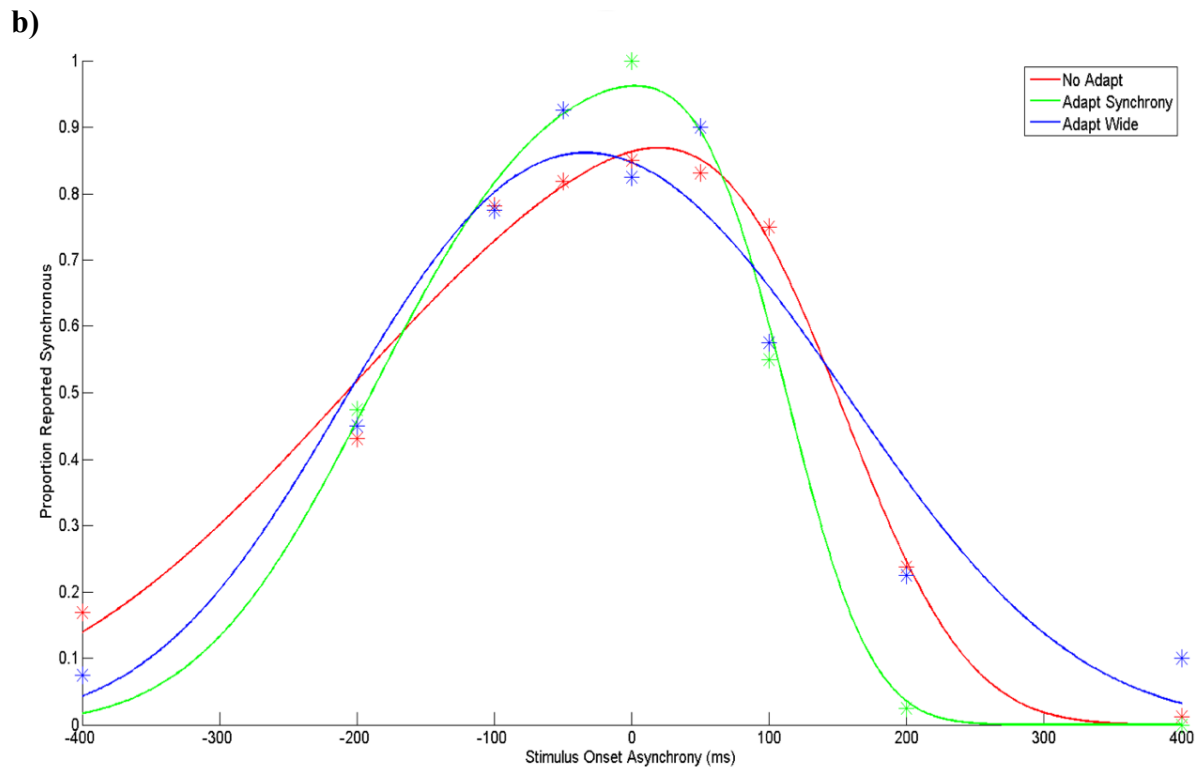
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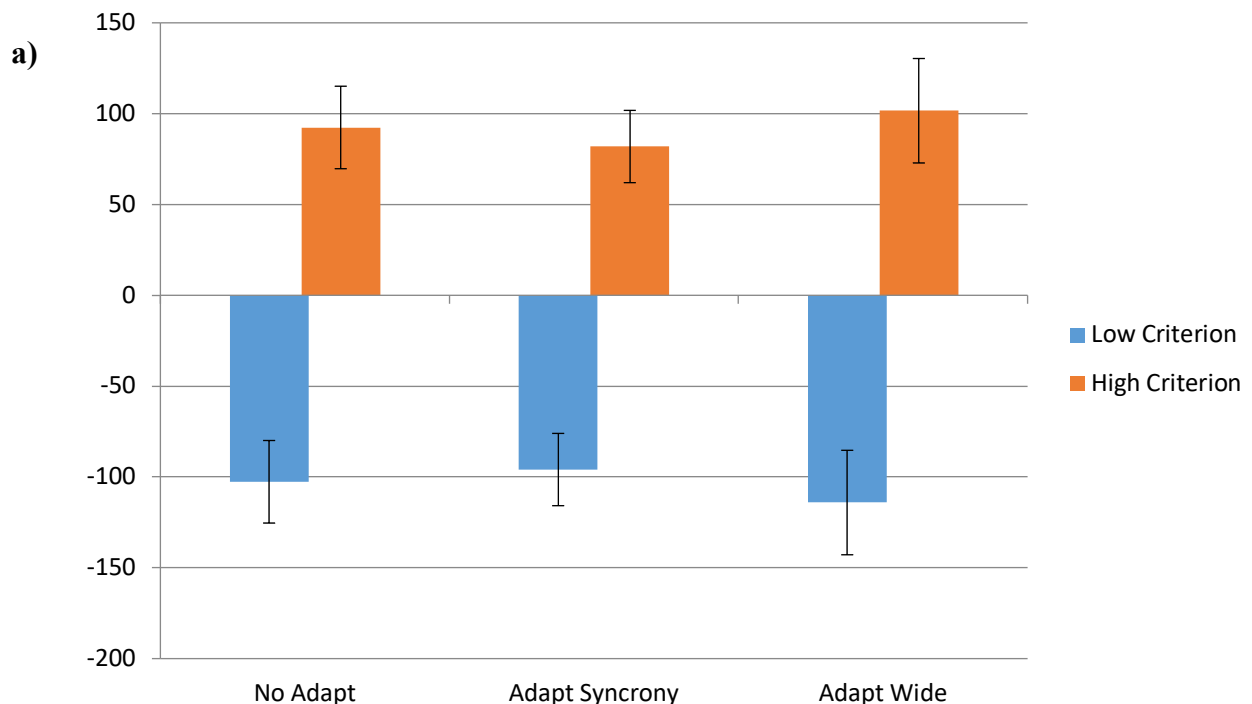
Figure 3: **(a),** Mean value of synchrony criteria for six observers under the three adaptation conditions. Low and high criteria represent the borders of simultaneity window. **(b),** The proportion of 'simultaneous' responses for representative observer JB and the fitted difference of two Gaussians for each of the three adaptation conditions.

(b) Change in precision for synchrony detection

Previously, repeated exposure to synchrony shown to improve sensitivity for discriminating synchrony out of asynchronous modalities in three-interval forced choice odd-one-out task (Roseboom et al, 2015). Thus, in a further analysis, we investigated whether or not adaptation condition had a significant effect on precision for discriminating synchrony. A 2 X 3 repeated-measures ANOVA conducted on synchrony criteria SDs with criteria side (low and high) and adaptation types (no adapt, adapt to audio lead, adapt to vision lead) taken as factors. ANOVA between the criterion sides revealed a non-significant relationship between the high and low criterion, $(F_{(1, 5)} = 0.06, p = .82, \eta^2 = .012)$. Further analysis in Bayesian ANOVA indicated weak evidence for the no-difference between the criteria sides ($BF_{10} = 0.375$, %$_{error} = 0.982$) (JASP Team, 2016). Therefore, mean SD values were symmetrical across both sides.

More interestingly, ANOVA revealed a main effect of adaptation on SD values, $F_{(1.03, 5.15)} = 24.47$, $p = .004$, $\eta^2 = 0.830$, suggesting that precision for discrimination of synchrony was modulated by the adaptation regime. To further explore the effects of different adaptation regimes on precision of synchrony judgments, we conducted post-hoc contrasts of synchrony criteria SDs in each adaptation condition. Comparison of SD values for the three adaptation regimes revealed that precision in discriminating synchrony from asynchrony was enhanced following synchrony-adaptation ($M_{low} = 56.33$, $M_{high} = 53.64$) compared to no-adaptation ($M_{low} = 90.79$, $M_{high} = 80.58$; $p_{bonf} < .001$). Figure 4 shows the raw data combined from all participants in each condition. On the other hand, reciprocal changes (worsening) in precision following wide adaptation were not observed ($p_{bonf} = 0.885$). As in, SD values following wide adaptation ($M_{low} = 77.80$, $M_{high} = 83.19$) were not statistically different than SD values for the no-adaptation condition ($p_{bonf} = 0.885$). However, there was a significant difference between adaptation to wide and adaptation to synchrony conditions in favor of synchrony having lower SD ($p_{bonf} < .001$). Altogether, these results show that precision in discriminating synchrony was improved following synchrony exposure, consistent with previous findings in the literature (Roseboom et al, 2015). However, it should be noted that there was no evidence for a difference in precision for categorizing synchrony following the wide exposure.
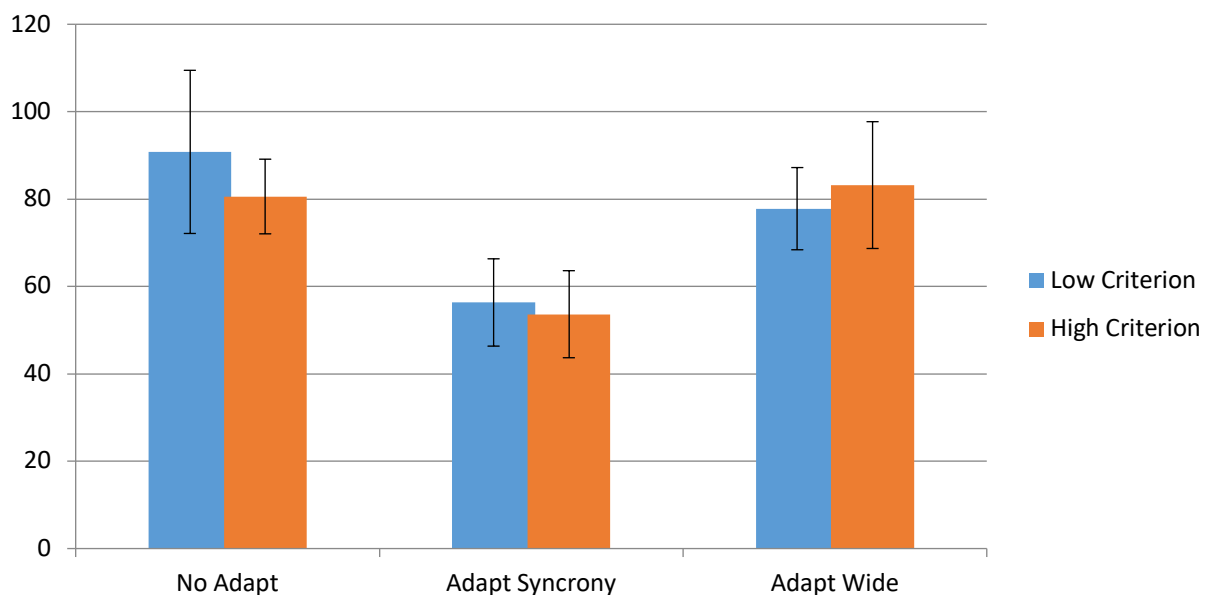

Figure 4: Bar plots depicting the mean standard deviation (SD) of synchrony criteria for six observers under the three adaptation conditions. Low and high criteria represent the borders of simultaneity window from both sides.

Magnitude Estimation Task

Mean observer estimates of audiovisual asynchronies under different adaptation regimes are illustrated in figure 5. In order to assess the main effect of adaptation on perceptual reports, a 3 X 9 repeated-measures ANOVA analysis for the nine values of SOA (±400, ±200, ±100, ± 50 and 0 ms) and three adaptation conditions (adapt to synchrony and adapt to wide, no-adapt) was conducted. Comparison between SOA values revealed a significant main effect of SOA on perceptual reports ($F_{(8, 40)} = 73.471$, $p < .001$, $\eta2 = 0.936$) as is expected given that these values are physically varied and participants were pre-trained to identify them. However, no main effect of adaptation was revealed ($F_{(2, 10)} = 0.306$, $p = 0.743$, $\eta2 = 0.058$), nor an interaction involving adaptation and SOA ($F_{(16, 80)} = 1.104$, $p = 0.366$, $\eta^2 = 0.181$). Furthermore, Bayesian analysis provided strong evidence for no-main effect of adaptation on perceptual reports ($BF_{10} = 0.062$, $\%_{error} = 1.741$) (JASP Team, 2016). Taken together, these results indicate that there was no differential effect of adaptation regime on estimated SOA (see figure 5).
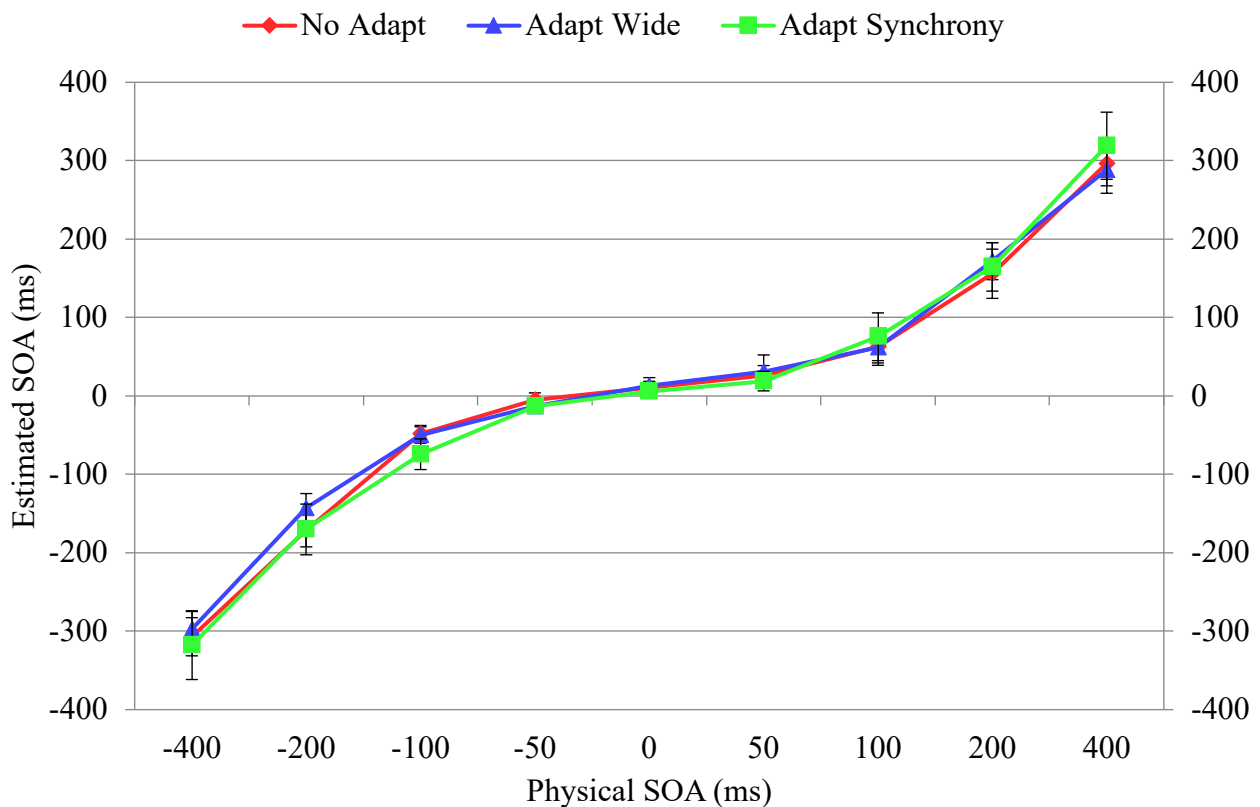
Figure 5: Results of magnitude estimation task 1.**,** Magnitude estimates averaged across six observers for each physical SOA following adaptation adaptation to synchrony (green lines), adaptation to wide asynchronies (blue lines), and no-adaptation (red lines). Estimated SOA represented the reported temporal asynchrony between the visual and auditory stimuli on a given trial, with negative values indicating that the auditory stimulus preceded the visual, and positive values indicating the auditory stimulus trailed the visual. Absolute time estimates averaged across 9 observers for each physical SOA following adaptation to a visual lead of 400 ms (blue lines), adaptation to audio lead of 400 ms (green lines), and no-adaptation (red lines).

2.3. Discussion

Assuming the magnitude estimation task is a more accurate index for measuring relative time perception, we set out to answer the following question: Do simultaneity judgments involve non-temporal processes that are sensitive to different adaptation regimes?

Observers completed three adaptation conditions (baseline, adapt-synchrony, adapt-wide-asynchrony) for both tasks separately. Adaptation regimes differed in the way audio and visual signals distributed while having identical zero-ms means, which therefore would not be expected to generate strong changes in representation of sensory processing of time. In line with this proposal, we found evidence that SOA estimates for magnitude estimation task were insensitive to prior-exposure (see figure 5). Perceptual changes measured by SJ-task were twofold.

(1) Assuming people have fairly vague internal anchors for simultaneity, we predicted that distribution regimes of adaptation would produce changes in simultaneity criteria, without producing a change in sensory processing level of the signals (Di Luca et al, 2009; Navarra et al, 2009). We found that simultaneity criteria for all three condition were not significantly different. However, results summarized above indicate that current data were not sensitive enough for to differentiate synchrony criteria in the different adaptation conditions. Although similar findings were previously demonstrated with sample sizes similar to here (Di Luca et al, 2009; Hanson et al, 2008; Roseboom et al, 2015, 2009), lack of statistical power for the current analysis suggest that sample size were too small to detect an underlying effect.

(2) Furthermore, we looked at the changes in observers' precision for detecting synchrony in all three adaptation conditions. As expected, observers judged simultaneity with greater precision following adaptation to synchrony compared to baseline condition, while discrimination ability was not significantly different between no-adaptation and wide adaptation. These results are in line with recently demonstrated exposure-induced changes in sensitivity for performance in three-interval odd-one-out task (Roseboom et al, 2015). However, unlike Roseboom et al's finding in changes of sensitivity in performance for finding the odd one, here we showed the similar changes in sensitivity for judgments about the *appearance* of the simultaneity.

Perceptual changes observed in SJ-task could also captured with the population-code analysis (Heron et al, 2012a; Roach et al, 2010; Roseboom et al, 2015). That is exposing to a wide distribution should disperse the selective deactivation of individual neurons while exposure to the pointy distribution would lead to a local deactivation of neurons for the adapted values to the extent that observers could adopt a more conservative simultaneity window compared to no adaptation.

In summary, the discrepancy in performance measured between magnitude estimation and SJ-task suggests that simultaneity judgments involve decisional processes operating on the outcome of timing processes that are identical under both metrics of time (Yarrow et al, 2011, 2015). Thereby, findings of the present study would support re-evaluating the credibility or relevance of simultaneity judgments on time perception (Donohue et al, 2010; Yuan & Huang, 2015; Sekuler et al, 1997; Zampini et al, 2005).

3. Experiment 2

To further investigate the mechanisms involved in exposure-induced temporal recalibration, here we sought to investigate the relationship between absolute time and relative time encoding in propagating lag adaptation.

3.1. METHODS

Experimental design and the stimulus apparatus were identical to experiment 1, except for the following changes.

(a) Participants

Nine observers (four male, five female, age: 22–29 years) participated in the experiment. Observers included one of the authors (G.E) and eight further participants, who were naive as to the experimental purpose. Informed consent was obtained from all participants before the experiment in accordance with the University of Sussex Ethics Committee.

(b) Procedure

To investigate a possible dissociation between relative time encoding and absolute time encoding or an interaction between them, a new type of behavioral task was introduced. In one experimental condition, observers were explicitly asked to disregard the direction of temporal relationship between audio and visual signals, instead they were asked to report only the observed absolute time difference between audio and visual signal regardless of the order of presentation (e.g. estimate the duration between the sensory events), while in the other condition, they were asked to estimate the relative time for audiovisual asynchronies (e.g. judge the temporal order between audio and visual signals and include it on your estimation of how far apart are they).

As depicted in figure 6, in half of the four-session set, participants estimated the apparent relative time difference between audio and visual signals (identical to the experiment 1), while in the other half, they were asked to estimate only the absolute time difference between audiovisual pairings. The order in which the two tasks were executed was counter-balanced across observers. In both tasks, observers were asked to estimate the SOA between pairs of brief auditory and visual stimuli with and without prior adaptation to a fixed asynchrony (400 ms visual-lead or 400 ms auditory-lead). Participants responded by adjusting a set of sliders with the mouse.
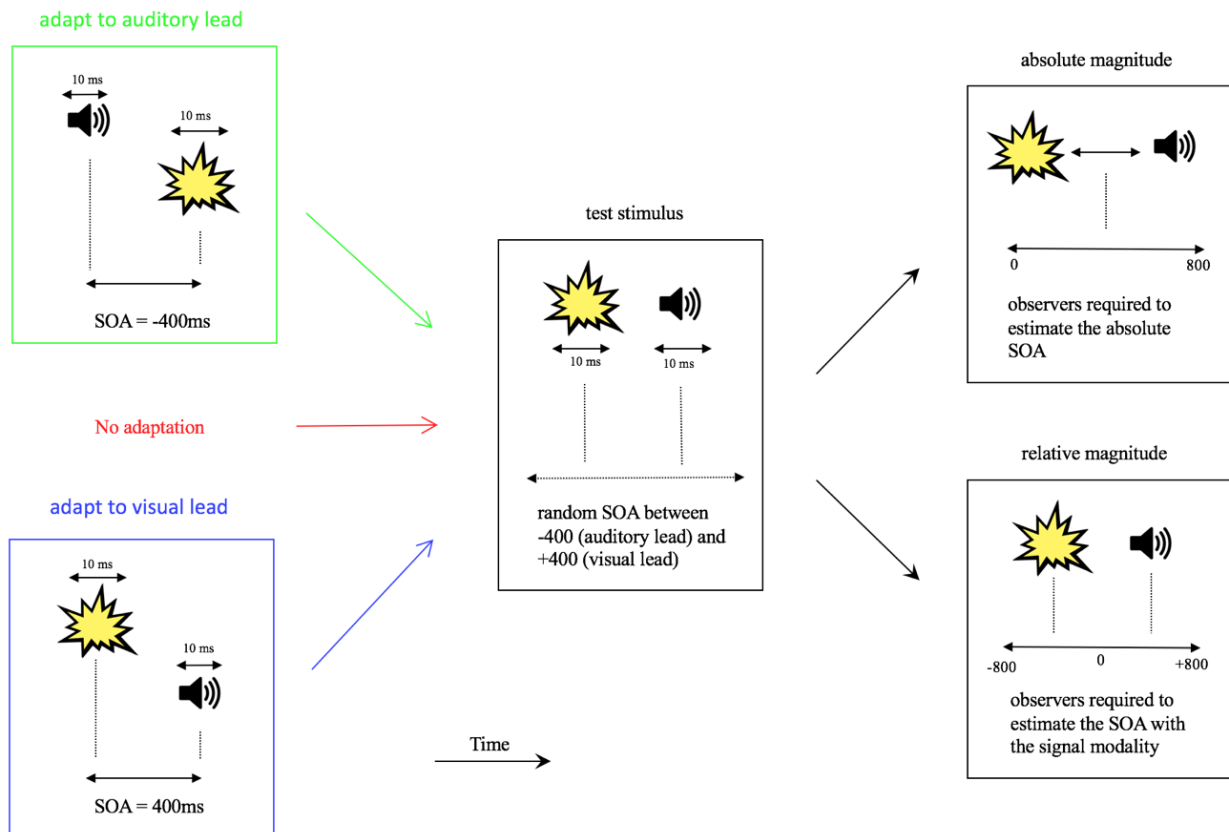
Figure 6. Schematic representation of the experimental sequences designed to investigate the exposure-induced changes in perceived timing over a range of stimulus-onset-asynchronies (SOA). See the main text for details.

3.2. RESULTS

(a) Changes in absolute timing estimation

The absolute time reports in response to the temporal differences in both sensory modalities are illustrated in Figure 7. A 3 x 5 repeated measures ANOVA with the five SOA levels (0, 50, 100, 200, 400) and three levels of the adaptation factor (audio leading visual by 400ms, visual leading audio by 400ms, and no-adaptation) were conducted. Mauchly's test indicated that the assumption of sphericity was violated for the main effect of adaptation, $\chi^2(2) = 8.218$, $p = .016$, and SOA, $\chi^2(9) = 35.875$, $p < .001$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .59$ for the main effect of adaptation and .36 for the main effect of SOA). Contrary to the difference observed in initial inspection of the raw data in figure 7, ANOVA revealed no main effect of adaptation (F(1.18, 9.46) = 1.70, p = 0.227, $\eta^2 = 0.176$), but a main effect of physical SOA on absolute time estimations

(F(1.46, 11.71) = 99.60, p < .001, η^2= 0.926). Interestingly, a significant interaction involving SOA and adaptation were revealed (F(2.17, 17.37) = 4.884, p = 0.019, η^2= 0.379), again using Greenhouse-Geisser correction (ε= .27). This indicates that the physical SOA had different effects on observers' estimates depending on the adaptation levels. For example, mean estimates for the visual leading audio by 400ms SOA with no adaptation condition (M = 339.60, SD = 72.28) were increased compared to mean estimates following adaptations to audio leading visual and adaptation to visual leading audio (M = 279.54, SD = 82.81; M = 312. 43, SD = 131.55, respectively)

In further analysis, Bayesian ANOVA revealed only anecdotal evidence for the null hypothesis regarding main effect of adaptation on absolute timing judgments (BF$_{10}$ = 0.386, %$_{error}$ = 1.259) (JASP Team, 2016). This result suggests that the data collected here were insufficient for a clear conclusion regarding the relationship between adaptation and absolute time estimation.
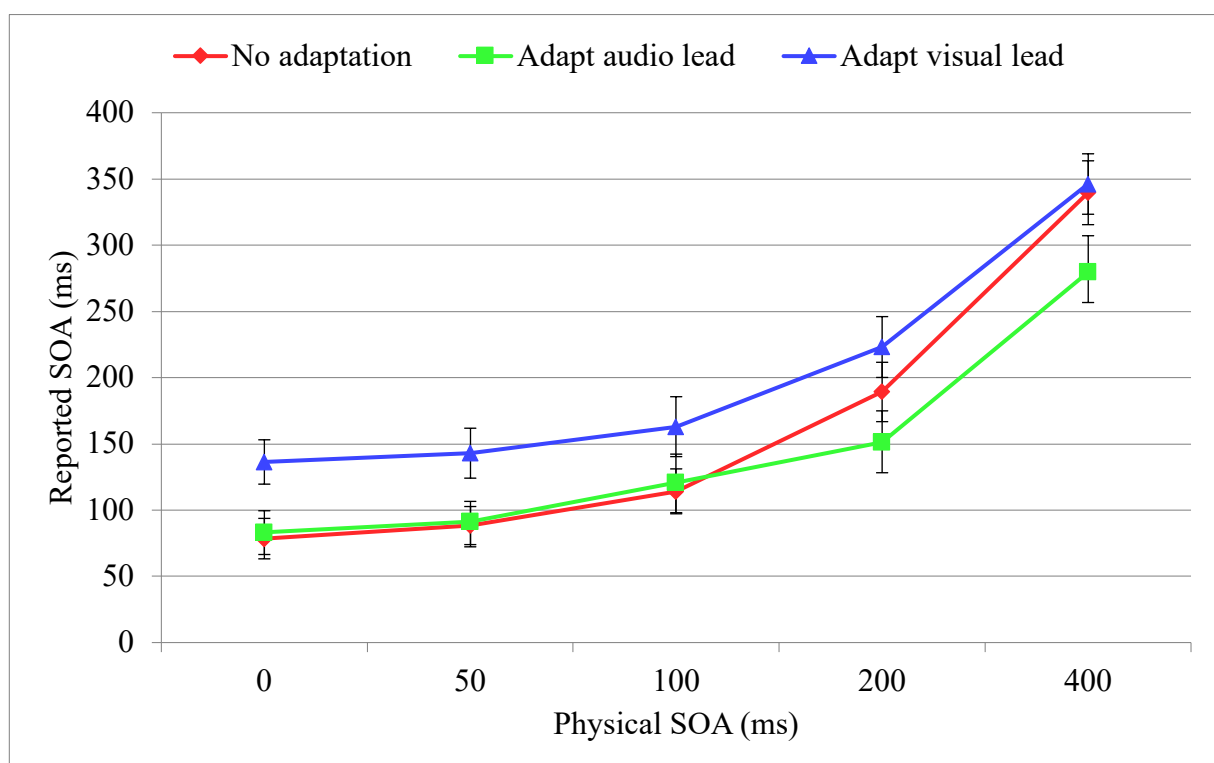
Figure 7: Absolute time estimates averaged across 9 observers for each physical SOA following adaptation to a visual lead of 400 ms (blue lines), adaptation to audio lead of 400 ms (green lines), and no-adaptation (red lines).

(b) Changes in relative magnitude estimation

The perceived relative time estimates in response to audiovisual asynchronies are depicted in Figure 8a. A 3 x 9 repeated measures ANOVA was carried out in order to investigate whether or not adaptation condition had an impact on relative timing estimation. There were nine values of SOA (±400, ±200, ±100, ± 50 and 0 ms) and three adaptation conditions (audio leading visual by 400ms, visual leading audio by 400ms, and no-adapt). As expected, ANOVA revealed that exposure to asynchronous audiovisual adaptation influenced the subsequent perception of temporal relationship in audiovisual event ($F_{(2, 16)}$ = 6.87, p = .007, η^2= 0.462). Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of SOA ($\chi^2(35)$ = 120.239, p = < .000). Therefore, degrees of freedoms were corrected using the Greenhouse-Geisser method (ε= .21). Consequently, a main effect of SOA on relative timing estimates was also revealed ($F_{(1.71, 13.704)}$ = 79.48, p < .001, η^2= 0.909). However, no significant interaction involving SOA and adaptation condition was found ($F_{(16, 128)}$ = 1.43, p = .137, η^2= 0.152). Taken together, results agreed with the hypothesis that the adaptation condition had an effect on observers' estimates of audiovisual asynchronies.

Post-hoc analyses with Bonferroni corrected t-tests were conducted on all possible adaptation couplings in order to investigate the direction of changes. Comparison between means indicated that following exposure to audio leading, observers' SOA estimation were increased in magnitude, compared to the baseline condition (M_{dif} = 24.06, p= .006,). This implies that on average, observers overestimated subsequent test trials following adaptation to audio leading vision, compared to no-adaptation. However, no significant difference was observed between no-adaptation and adaptation to vision leading (M_{dif} = 9.87, p = 0.449), nor between the two adaptation conditions (M_{diff} = 14.19, p = 0.135) (See figure 6a).
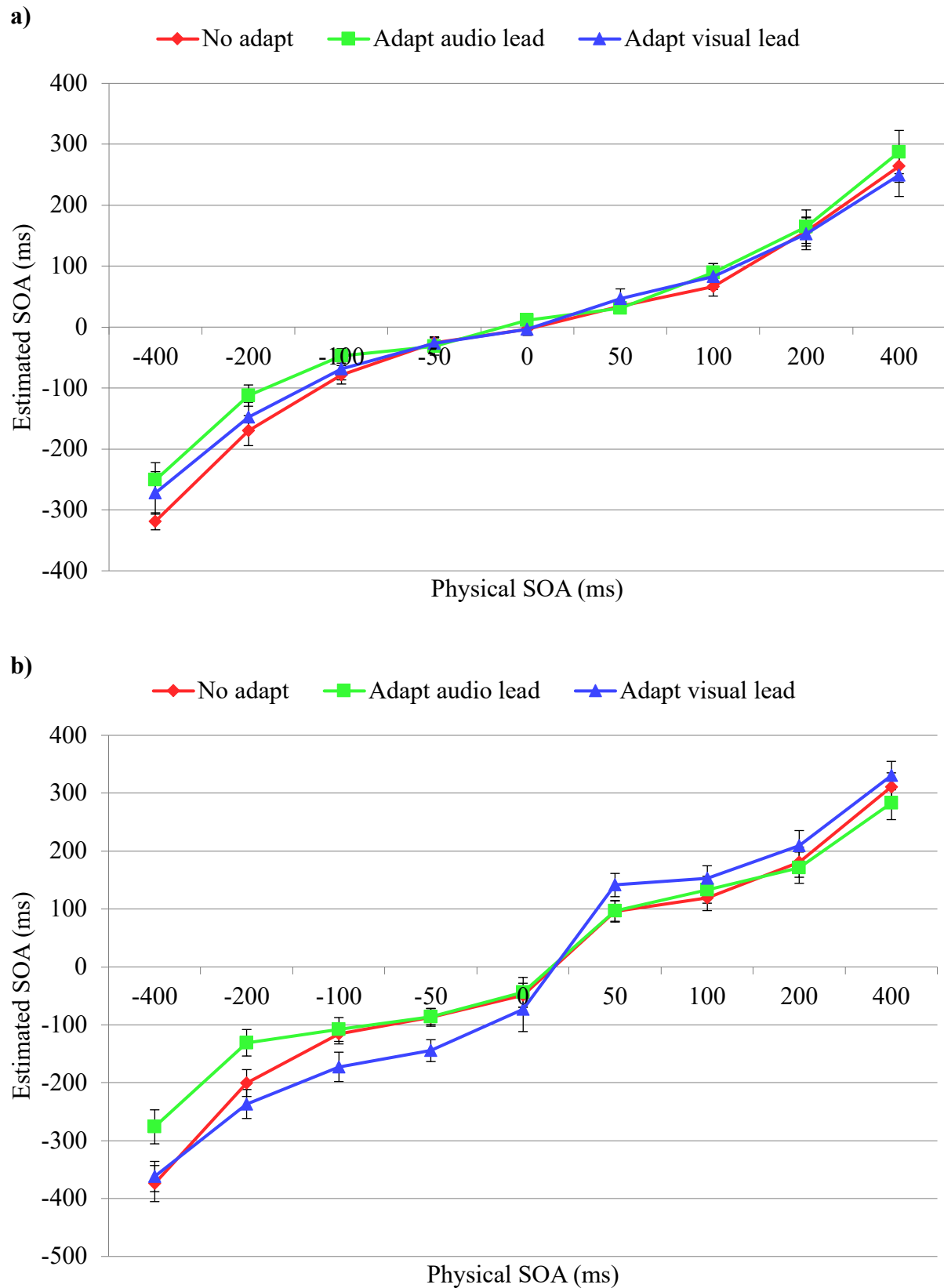
a)

b)

Figure 8: SOA estimates at each physical SOA averaged across 9 observers. Negative numbers indicate audio preceding visual. **a)** Reports of SOA estimates as a function of SOA

for the relative magnitude estimation task. **b)** Absolute timing estimates involving the same stimuli and design but converted to a relative scale for comparison.

(c) Comparison between tasks

Firstly, responses to absolute time estimation task were converted into the relative timing scale with the assumption that temporal order of the audiovisual events were estimated correctly by the observers. For example, absolute time estimation of 300 ms plotted as either -300 or +300, depending on the order of presentation of the different modalities (e.g. audio leads visual or vice versa). Figure 8b shows the absolute timing judgments converted into the relative scale. A 3 X 9 repeated measures ANOVA revealed a main effect of adaptation on perceived absolute-as-relative reports ($F_{(2, 16)} = 6.765$, $p = .007$, $\eta^2 = .458$). Unlike above reviewed analysis of variance in absolute timing estimates, results here imply that adaptation caused marked changes in observers' relative time perception, while they engage in absolute timing estimation.

Post-hoc comparison using Bonferroni correction revealed that mean estimates following the audio-leading asynchrony adaptation were significantly higher than estimates with no prior-adaptation ($M_{diff} = 17.52$, $p = .037$). However, reciprocal changes in SOA estimates were not observed following visual-leading asynchrony ($M_{diff} = 3.97$, $p = 1.00$). Furthermore, comparison between the two adaptation conditions revealed that estimates following audio-leading asynchrony adaptation were significantly higher than estimates following the visual leading audio adaptation ($M_{diff} = 21.51$, $p = .010$). Interestingly, this pattern of results is identical to those previously reviewed changes observed in relative time estimates. Taken together, mean estimates following adaptation to audio leading asynchronies were higher than the baseline, while there was no significant difference in mean estimates following visual leading asynchronies and of estimates with no adaptation.

There was also a main effect of SOA ($F_{(8, 64)} = 89.480$, $p = .001$, $\eta^2 = .918$, as well as a statistically significant interaction between SOA and adaptation type ($F_{(16, 128)} = 6.258$, $p = .001$, $\eta^2 = .439$). This therefore indicates that adaptation had different effects on SOA estimates depending on which physical SOA was presented. For example, mean estimates for the visual leading audio by 400ms SOA with no adaptation condition ($M = 311.05$, $SD = 72.31$) were reduced following adaptations to audio leading visual ($M = 282.96$, $SD = 85.65$),

but increased following adaptation to visual leading audio (M = 330.44, SD = 73.69).

(d) Changes in point of subjective simultaneity (PSS)

To directly compare the results in the two tasks we looked at the data as transformed into a binary classification of temporal order, as is the case for the classic temporal order judgment (Fujisaki, 2004; Hanson et al, 2008; Miyazaki et al, 2006; Sugita & Suziki, 2003; Vroomen et al, 2004). We calculated PSS by assuming a criterion for temporal order set at physical 0 ms. Consequently, any report of the SOA as less than 0 was taken as a report of audio before vision, and any after as vision before audio. These were then fit with a cumulative Gaussian as is the case for typical temporal order judgments and the 50% point were taken as the point of subjective simultaneity (Fujisaki, 2004; Hanson et al, 2008; Miyazaki et al, 2006; Vroomen et al, 2004; Yarrow et al, 2011). To assess the effect of task type on PSS, a 2 x 3 repeated measures ANOVA with factors as task (absolute and relative) and adaptation (no adapt, adapt to audio lead, adapt to vision lead) was conducted. ANOVA indicated a no main effect of task type on PSS, ($F_{(1, 8)}$ = 1.49, p = .257, η^2= 0.157), implying that mean PSS values in the relative magnitude task condition were not significantly different from absolute-as-relative task (see figure 9). However, Bayesian ANOVA indicated that the current data set were not sensitive for a clear conclusion regarding the main effect of task type. (BF_{10} = 1.191, %$_{error}$ = 0.772) (JASP Team, 2016).

Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of adaptation ($\chi^2(2)$ = 7.207, *p* = .027). Therefore, degrees of freedom were corrected using the Greenhouse-Geisser (ε= .61). Consequently, ANOVA also revealed no main effect of adaptation on observed changes in PSS ($F_{(1.22, 9.74)}$ = 0.70, p = .45, η^2= 0.81).This indicated that mean PSS was not significantly different across three adaptation conditions, irrespective of the task. In a further analysis, Bayesian repeated measures ANOVA revealed evidence for the null hypothesis (BF_{10} = 0.224, %$_{error}$ = 0.724) (JASP Team, 2016). Therefore, results indicated that when individual mean PSS values for adaptation condition were averaged for both task types, adaptation condition had no impact on mean PSS values across both tasks. More interestingly, we found no significant interaction involving the adaptation type and task type ($F_{(2, 16)}$ = 1.075, p = .365, η^2= 0.118). Bayesian ANOVA suggested an evidence for the null (BF_{10} = 0.289, %$_{error}$ = 1.554) (JASP Team, 2016). Taken

together, results show that mean PSS was not significantly affected by the adaptation condition.
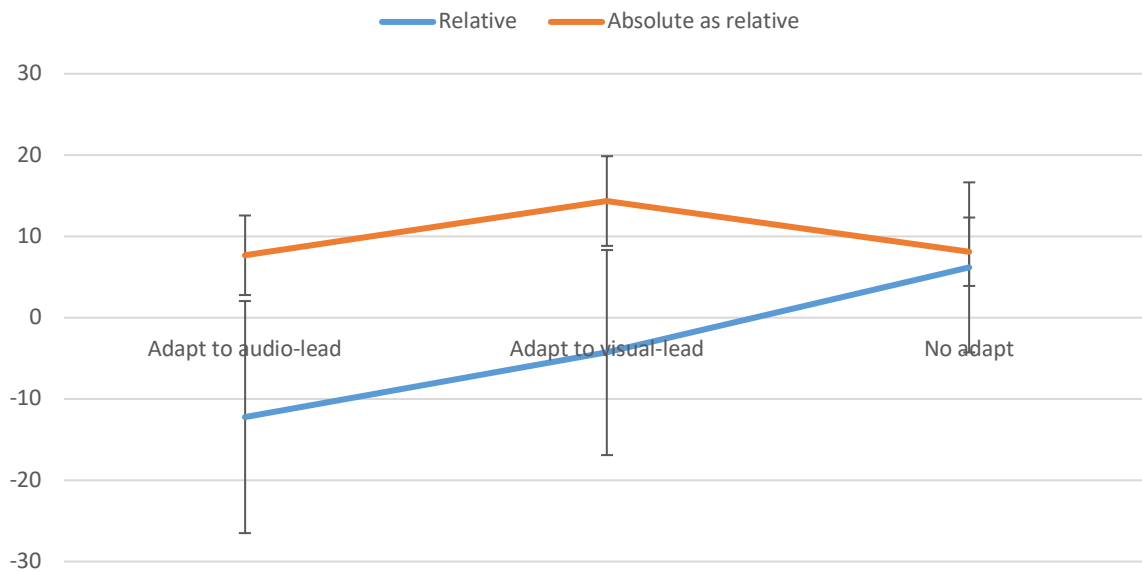

Figure 9: Scattor plots depicting the mean PSS values in response to adaptation conditions for nine observers for both relative (blue) and absolute-as-relative tasks (orange). Mean PSS values in the vertical negative axis indicates audio leading visual requirement for 'simultaneous', while positive values represent mean PSS values where visual leading audio is required.

3.3. Discussion

We investigated, for the first time, a possible dissociation between relative time encoding and absolute time encoding or an interaction between them in multisensory timing judgments. In particular, when observers disregard the temporal order and estimate only the absolute time difference between audio and visual signals, we expected to observe an identical adaptive shifts in estimates following repeated relative adaptations (audio-leading by 400ms and visual-leading by 400ms). That is, both asynchrony exposure would operate in absolute terms (400ms) and produce identical repulsive shifts for the subsequent timing percept. On the other hand, relative timing estimates following asynchrony exposure would produce repulsive shifts only for the SOA values in the same direction of the adapted signal modality (Roach et al, 2010, Yarrow et al, 2011, 2015).

Results showed that observers' absolute timing estimates following audio-lead, visual-lead and no adaptation were not significantly different. However, it should be noted that analysis presented evidence that the data set were not sensitive enough to conclude about estimates being the same. Taken together, present data did not provide support for the existence of exposure-induced changes in absolute time judgments.

On the other hand, results showed that when observers engage in relative magnitude estimation, their SOA estimates were in average overestimated following repeated audio-lead asynchronies. Although this finding appears analogous to exposure-induced changes in time relative time perception (Fujisaki et al, 2004; Hanson et al, 2008; Heron et al, 2007; Roach et al, 2010), reciprocal changes for the estimates following visual-leading adaption were not found. Why did we observe temporal recalibration following audio-leading adaptation but not in the others? One possible explanation for this asymmetrical recalibration in audiovisual asynchrony is that this asymmetry may be linked to the fundamental asymmetry in naturally occurring audio and visual signals. Given the faster neural transduction for audition over vision (Alais & Carlile, 2005), auditory signal must lag behind vision (~30ms) for us to perceive simultaneity. However, this auditory dominance over vision have a narrow range (~10m), to the contrary vision leads the auditory for the distant events. Considering we usually engage with audiovisual events in close proximity, recalibration shifts occurring in greater magnitude for sound leading adaptation is not surprising. However, this interpretation appears to contradict with the asymmetry observed in an earlier finding (Van der Burg et al, 2013). Van der Burg et al, demonstrated that the recalibration shift for vision leading was greater than auditory leading. However, the key difference between their study and the present one, lies on the type of task they used as well as the adaptation type they designed. Contrary to their experiment, we measured exposure-induced relative timing judgments in response to long top-up exposure phases, while they measured simultaneity judgments without prior top-up adaptation phase. However, further research on why do observers appear to possess asymmetrical recalibration mechanisms for auditory and vision is needed for a comprehensive understanding.

Interestingly, however, when absolute timing estimates were converted into relative timing scheme, adaptation types appear to play important roles in observers' estimates. That is, estimates following audio-leading asynchrony adaptation were systematically shifted away from the direction of the adapted modality, while no difference was observed following

vision-leading adaptation. This results are identical to previously reviewed changes observed in relative time estimates. Although, observers engaged in absolute timing estimation, it appears like asymmetry in relative timing recalibration still operates. However, another possibility for the observed differential effect of adaptation may have to do with the metric used for response production. Absolute time scale used in the experiment may have biased the responses towards the middle of the SOA values, as it was classically referred as 'regression effects' in the literature (Stevens & Greenbaum, 1966; Roach et al, 2010). Raw responsed depicted in the figure 5, highlights the possibility of the attraction in observers' responses towards the middle values. (see figure 5). However, when the data converted into relative timing scheme, naturally occurring asymmetrical recalibration and response biases may interact in a unique way. These findings certainly deserve a closer examination in future studies.

A potential shortcoming of this study may have to do with the adaptation design. As detailed in procedure, baseline condition (no-adaptation) were compared to adaptation conditions (auditory lead, visual lead) with the assumption that the differences in estimates would show the magnitude of the adaptation effect. However, responses to test trials in no-adaptation block may reflect susceptibility to the previously reported values, while having top-up adaptation phase in between the responses would arguably weaken the response bias. One way to overcome the response biases affiliated with the baseline (no-adapt) condition is to use neutral adaptation condition. Estimates following synchrony-exposure would be an appropriate candidate for a baseline condition to measure the effect of asynchrony exposure on relative time judgments (Yarrow et al, 2011). Having said that, exposure to synchrony may further complicate the interpretation of the differences between conditions. Therefore, adding both adaptation to synchrony and no-adaptation regimes together into the experimental design would be the best (Yarrow et al, 2015).

4. General Conclusion

We extended the model of temporal recalibration observed in relative-timing judgments by demonstrating the how adaptation regimes and task types modifies the performance of subjective timing estimates. The most important result emerged from the analysis of Experiments 1 and 2, was the finding that exposure-induced changes in relative timing judgments of audiovisual stimuli depend not only on the sensory representation of the

temporal relationship, but also on decisional factors, judgment strategies, and/or any response biases adopted by observers. Therefore, these findings provide fundamental insights on the mechanisms underlying our perception of relative time. More research is needed to further resolve the association between absolute time and relative time encoding in exposure-induced subjective timing estimates.

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