



Where and when to look: Sequential effects at the millisecond level

José Eduardo Marques-Carneiro¹ · Patrik Polgári¹ · Estelle Koning¹ · Emilie Seyller¹ · Brice Martin² · Erik Van der Burg^{3,4} · Anne Giersch¹

Published online: 4 March 2020
© The Psychonomic Society, Inc. 2020

Abstract

Learning and imitating a complex motor action requires to visually follow complex movements, but conscious perception seems too slow for such tasks. Recent findings suggest that visual perception has a higher temporal resolution at an unconscious than at a conscious level. Here we investigate whether high-temporal resolution in visual perception relies on prediction mechanisms and attention shifts based on recently experienced sequences of visual information. To that aim we explore sequential effects during four different simultaneity/asynchrony discrimination tasks. Two stimuli are displayed on each trial with varying stimulus onset asynchronies (SOA). Subjects decide whether the stimuli are simultaneous or asynchronous and give manual responses. The main finding is an advantage for different-order over same-order trials, when subjects decided that stimuli had been simultaneous on Trial $t - 1$, and when Trial t is with an SOA slightly larger than Trial $t - 1$, or equivalent. The advantage for different-order trials disappears when the stimuli change eccentricity but not direction between trials (Experiment 2), and persists with stimuli displayed in the centre and unlikely to elicit a sense of direction (Experiment 4). It is still observed when asynchronies on Trial $t - 1$ are small and undetected (Experiment 3). The findings can be explained by an attention shift that is precisely planned in time and space and that incidentally allows subjects to detect an isolated stimulus on the screen, thus helping them to detect an asynchrony.

Keywords Temporal processing · Visual perception · Attention shift · Prediction · Temporal sequences · Sequential effects

We can follow visual information in a seemingly fluid way, even when it is complex. For example, we can follow sequences of movements accurately in both space and time (Repp & Su, 2013; Su & Salazar-López, 2016). Kang, Lancelin, and Pressnitzer (2018) recently showed that

sequences of lights displayed at random intervals of tens of milliseconds (ms) can be easily learned, suggesting that recent experiences guide our attention in time and space. A high temporal resolution of visual perception certainly matches our impression of time fluidity in our movements, but also in the visual environment.

Yet many aspects of conscious visual perception seem slow and are not well suited for high temporal resolution performance (Elliott & Giersch, 2016; van Wassenhove, 2009). For example, a stimulus-onset asynchrony (SOA) of ~30 ms is usually required for two stimuli to be consciously distinguished in time. For attention to be shifted between the two stimuli requires an even longer delay of approximately 100 ms (Deubel, 2008). Several studies additionally suggest that attention is rhythmic (i.e., discontinuous). This has first been proposed in the context of the dynamic attending theory and applied to sounds (Large & Jones, 1999, for a review). In vision, attention may also be cyclic rather than continuous (Fiebelkorn, Pinsk, & Kastner, 2018; Helfrich et al., 2018; Van Rullen, 2018). These studies are consistent with those suggesting that object processing is slow and that perception

✉ Anne Giersch
giersch@unistra.fr

¹ Université de Strasbourg, INSERM U1114, Pôle de Psychiatrie, Fédération de Médecine Translationnelle de Strasbourg (FMTS) Centre Hospitalier Régional Universitaire of Strasbourg, 1, pl de l'Hôpital, 67000 Strasbourg, France

² Centre Ressource de Réhabilitation psychosociale et de remédiation cognitive, Centre Référent Lyonnais en Réhabilitation et en Remédiation cognitive (CL3R) Hôpital du Vinatier; CNRS UMR 5229, Lyon, France

³ TNO, Netherlands Organization for Applied Scientific Research, Soesterberg, Netherlands

⁴ Brain and Cognition, University of Amsterdam, Amsterdam, Netherlands

is discrete rather than continuous (Elliott & Giersch, 2016; Herzog, Kammer, & Scharnowski, 2016; Scharnowski et al., 2009). The possibility that attention is cyclic, and perception discrete, is in contradiction with our strong feeling of time continuity (Dainton, 2017). As a matter of fact, we do not experience a difficulty to follow events over time. The contradiction between the discreteness of perception and the strength of our sense of time continuity, however, requires an explanation. We have previously proposed that subconscious prediction of visual information at the millisecond level may compensate for the time resolution limitations of our visual attention and consciousness systems (Poncellet & Giersch, 2015) and here we verify the existence of such prediction mechanisms. It is beyond the scope of the present study to relate these mechanisms with the sense of time continuity, but this question is at the background of the present study.

Several studies reporting that perception occurs at high temporal resolution have typically used synchrony/asynchrony discrimination paradigms, whereby two visual stimuli are displayed at different spatial locations (Giersch et al., 2015; Lalanne, van Assche, & Giersch, 2012; Lalanne, Van Assche, Wang, & Giersch, 2012). Typically, the two stimuli were presented on the screen across a range of SOAs, and the participants were instructed to report whether these events were presented in synchrony or not. Interestingly, these studies reported that subjects biased their response to the location of the second stimulus. Importantly, this bias was even observed for asynchronies smaller than 20 ms. This is intriguing, because temporal asynchronies of this order are typically not visible (Poncellet & Giersch, 2015; van Wassenhove, 2009).

A bias to respond towards the side of the last stimulus was explored more systematically by means of a priming paradigm (Poncellet & Giersch, 2015). In the Poncellet and Giersch (2015) study, two empty squares (placeholders) were shown, and subsequently followed by a target in one of the placeholders after 50 to 100 ms. The placeholders were either simultaneously or asynchronously presented, with an undetectable delay of 17 ms. Participants were faster when the target was displayed in the second placeholder than when it was shown in the first. This effect was interpreted as the result of an automatic shift of attention towards the location of the second placeholder (Poncellet & Giersch, 2015). We tentatively proposed that the shift of attention is driven by an unconscious prediction of the sequence of two placeholders (see Poncellet & Giersch, 2015, for a detailed discussion). Such predictions would be based on recent experiences of asynchronies (i.e., on trial-to-trial effects). Because a series of trial-to-trial effects have been described in the timing literature, we briefly describe those before detailing our hypotheses for the present work.

To date, many studies have reported sequential effects in the temporal domain, demonstrating that the timing between visual events on a given trial depends on the timing between two visual events on the preceding trial. For instance, in the

variable foreperiod task, a target appears after a warning stimulus with variable delays, and subjects have to respond to the target as fast as possible. The probability that the target is displayed (the ‘hazard function’) increases with the increasing warning stimulus–target delay, resulting in increasing expectation and shorter reaction times (RTs) as the warning stimulus–target delay increases (Niemi & Näätänen, 1981). However, RTs also vary as a function of the events occurring on the preceding trial (Los & van den Heuvel, 2001; Los, Kruijne, & Meeter, 2017; Vallesi, Lozano, & Correa, 2013; Steinborn, Rolke, Bratzke, & Ulrich, 2008). The foreperiod (i.e., the time between the warning stimulus and the target stimulus) of the preceding trial influences performance on the current trial (t): If the foreperiod on Trial t is shorter than that on the previous Trial ($t - 1$), reaction times are slowed down. It is as if the preparation for a long interval leads to a surprise effect when the target appears earlier than expected. The precise mechanisms underlying this effect are still debated (see Los et al., 2017, for a review). The sequential effects might reveal a change in the evaluation of the target occurrence probability, which informs the system when to prepare (Niemi & Näätänen, 1981). Preparation itself may also be adjusted as a function of recent experiences, as if those would be replayed (Los et al., 2014; Los et al., 2017).

Whatever the precise mechanisms of these preparation adjustments, the idea that previous sequences are replayed, or at least that the system readjusts according to previous experience, may apply to events occurring at higher time resolution. Sequential effects have already been reported for brief asynchronies of less than 100 ms, in case of audiovisual stimuli. It has been shown that thresholds for asynchrony detection are adapted from trial to trial, so that the detection of the asynchrony is minimized (Harvey, Van der Burg, & Alais, 2014; Van der Burg, Alais, & Cass, 2013; Van der Burg & Goodbourn, 2015). These results suggest that asynchronies are detected and adjusted very rapidly and automatically. This effect, known as *rapid temporal recalibration*, occurs after passive (i.e., when a response is not required on Trial $t - 1$) as well as incorrect trials (i.e., participants perceive the order of the preceding trial incorrectly; Van der Burg et al., 2013; Van der Burg, Alais, & Cass, 2018). Such mechanisms would be used to optimize multisensory integration, whereby auditory and visual information is bound into a single percept when coming from a single source, such as, for example, in spoken language (Van der Burg & Goodbourn, 2015). Other mechanisms, however, may be required to follow unimodal visual information. Detecting fine-grained asynchronies may be useful in order to perceive and reproduce the subtle delays that compose complex gesture sequences, for example. This need (i.e., following information in time dynamically) is different from the need to integrate pieces of information into one unified percept. Thus, it would not be surprising if the effects of attention shifts differed from the recalibration effects.

In the present study, we will explore sequential effects in simultaneity/asynchrony discrimination tasks, during which two stimuli are displayed on the screen and subjects decide whether they are simultaneous or asynchronous. Based on our previous work (Lalanne, Van Assche, & Giersch, 2012; Lalanne, Van Assche, Wang, & Giersch, 2012; Poncelet & Giersch, 2015), we will investigate whether the perceived synchrony on a given Trial t is dependent on the order (space) and the asynchrony (time) of the previous Trial $t - 1$. Beyond a relatively trivial facilitation in the case of two successive trials sharing the same spatial properties (order), we hypothesize that the recent experience of asynchronous stimuli will induce the expectation of a sequence of stimuli similar in both space and time and hence induce attention shifts ahead of the expected stimuli. Such attention shifts may explain why subjects, when trying to detect onset asynchronies between stimuli, sometimes perceive a stimulus in isolation (i.e., before the second stimulus is shown). In return, the facilitation in asynchrony detection that is observed when a stimulus is perceived as being alone on the screen may reveal attention shifts. Attention shifts that are anticipated on the basis of the previous trial should be triggered by the first stimulus of the present trial, which can be a temporal trigger signaling the beginning of the sequence of two successive stimuli. The location of this first stimulus cannot be taken into account to adjust the prediction of the second stimulus location because there is not enough time between the two stimuli to adjust predictions. However, the second stimulus can be predicted to occur in the same location as in Trial $t - 1$, and around the same time after the first stimulus as on Trial $t - 1$. It follows that attention will be at the right place to detect one single stimulus only when the first stimulus of Trial t is in the location of the second stimulus of Trial $t - 1$ (i.e., when the direction has changed between the two trials; see Fig. 1). In addition, attention will be focused at the right moment to detect the single stimulus when the second stimulus is displayed slightly later than expected (i.e., when the SOA is longer than on the previous trial).

In Experiment 1, we investigate the possibility of attention shifts, by verifying the hypothesis illustrated in Fig. 1: After the first stimulus, which triggers the onset of the sequence, attention is shifted in space and time according to the previous trial, in order to attend to the second stimulus. When order is reversed on the present trial, attention ends up in the location of the first stimulus of the present sequence. This first stimulus is perceived as isolated on the screen if the second stimulus occurs later than on the previous trial, thus facilitating the detection of an asynchrony. In Experiment 2, we verify whether effects depend on the location of the predicted target: If the predictions based on recent experience involve attention shifts towards a specific stimulus location, then effects should disappear when the stimuli location changes. In Experiment 3, we examine whether the trial-to-trial effects also occur when the SOAs are too short to get noticed. Finally, we have seen

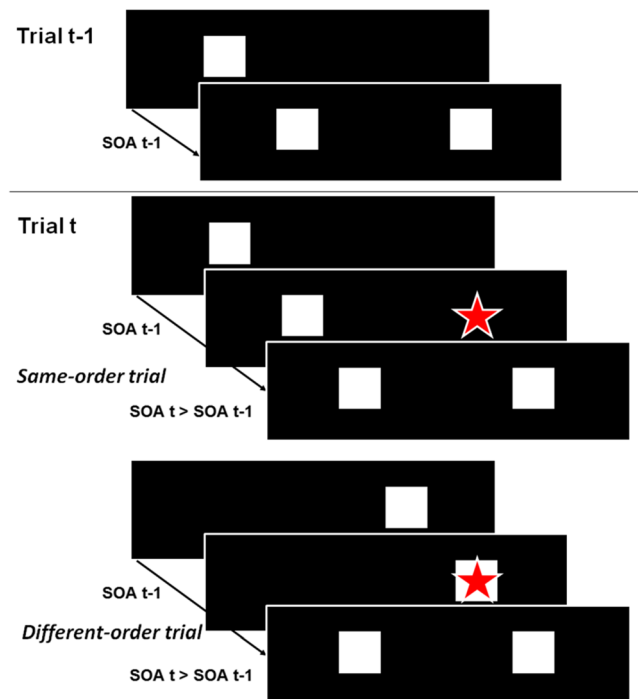


Fig. 1 Sequential effects expected if Trial $t - 1$ is used to predict where and when the stimuli are presented on Trial t , and attention is displaced according to the spatial and temporal characteristics of Trial $t - 1$. Trials $t - 1$ are shown in the top section, whereas corresponding Trials t with longer SOAs are shown in the bottom section. Same-order trials are shown in the middle, and different-order trials in the lowest part. On Trial t , attention, illustrated by the red star, is shifted toward the location of the second square of Trial $t - 1$, at the same time after the onset of the first square as on Trial $t - 1$. As a result, attention is optimally focused on the first square of Trial t only when the two trials have different orders and when the SOA is slightly longer on Trial t than on Trial $t - 1$ (i.e. the second square is presented later than expected)

that many sequential effects have been described in tasks involving timing, but here we explore the hypothesis of attention shifts, which differs from recalibration or adaptation. If this is true, then we may observe attention shifts' related sequential effects even in the absence of recalibration effects. Experiment 4 is aimed at testing this possibility by using data in which recalibration effects have been discarded (Harvey et al., 2014) and test whether sequential effects can be found similar to those observed in Experiments 1 to 3.

Experiment 1

The aim of Experiment 1 was to examine whether the perceived (or undetected) asynchrony on the previous trial affects the perceived synchrony on the current trial. In the experiment, participants saw two visual events across a range of asynchronies, and participants were instructed to make a synchrony judgment. If the asynchrony on the previous trial induces an attention shift according to our hypothesis (see Fig. 1), then there should be an improvement of performance

specifically when the order of stimuli is reversed from Trial $t-1$ to Trial t , and when the SOA is larger on the present trial than on the previous trial. Alternatively, a general priming effect was expected to induce a general facilitation whenever the two successive trials share the same order, and conversely, a general adaptation effect was expected to induce a general impairment. Because our first hypothesis led us to expect distinct types of results according to the difference in SOAs on successive trials, we analyzed the results with ANOVAs (i.e., by considering the SOA differences as categories). Although this might appear as maladapted for a variable that is continuous in essence, we considered that our analysis was severe enough and the only one adapted to verify our hypothesis.

Method

Participants

Experiment 1 was conducted with 14 students from the University of Lyon, or members of the laboratory. They were between the ages of 18 and 33 years ($M_{\text{age}} = 25.2$ years, $SD = 6.9$ years, 12 females, two males). The subjects were naïve as to the purpose of the experiment. All the participants had normal or corrected-to-normal visual acuity. None had any neurological or serious somatic disease or had taken any narcotics or drugs affecting the CNS. The project was approved by the local ethics committee in Lyon. Participants provided written informed consent prior to inclusion in the study, in accordance with the Declaration of Helsinki.

Equipment

Experiment 1 was run on a Pentium PC 4 and programmed using MATLAB 7.0.1 (The MathWorks, 1984–2004) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli were displayed on a 14-inch CRT monitor (60 Hz refresh rate). The experiment was conducted in a mesopic environment (0.1 cd/m^2 ; daylight did not enter the room). The distance between the screen and the participants was held constant, at 60 cm, by means of a chin rest.

Stimuli

The central blue fixation point was a circle with a diameter of 0.3° of visual angle. Stimuli were two grey rectangles (width 0.5° , height 1.5°), one displayed on the left side of the screen and the other on the right (4.5° from the screen centre). The luminance of the rectangles increased gradually from 0.03 (background luminance) to 12 cd/m^2 , over a presentation interval of 119 ms. The luminance was increased gradually to avoid magnocellular pathway activation (see also Giersch et al., 2009). The background was black (0.03 cd/m^2) and kept constant during the course of the experiment.

Procedure

Each trial began with the presentation of the fixation point that remained on the screen until the end of the trial. After a randomly determined delay of between 500 and 700 ms, the two left and right target rectangles were displayed across a range of SOAs (from 0 to 133 ms by steps of 16.7 ms). On half of the trials, the left target appeared before the right target, and on the remaining trials, the order was reversed. The target rectangles stayed on the screen until subjects made an unsped response, by either pressing the left or right response key when the rectangles were presented synchronously or asynchronously, respectively. The subsequent trial was initiated after 500 ms. Each combination of target order (right–left and left–right), and SOA (nine levels: 0, 17, 34, 51, 68, 85, 102, 119, and 137 ms) was tested 20 times in a randomly determined order, yielding a total of 360 trials.

Results

Sequential effects as a function of the SOA difference between Trials $t-1$ and t

The first trial of each block was discarded from further analyses. Furthermore, trials were collapsed over left-target-first and right-target-first trials, as we do not expect an asymmetry in the synchrony distribution. The results of Experiment 1 are shown in Fig. 2. Here, the mean percentage of asynchrony responses is plotted as a function of the SOA difference

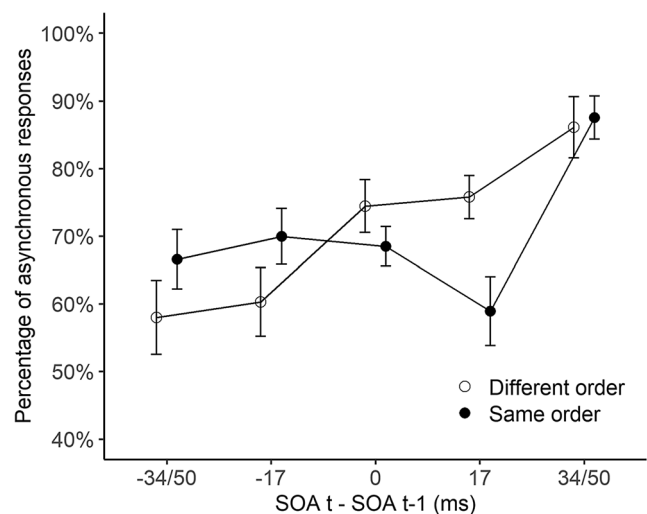


Fig. 2 Results of Experiment 1. Mean percentage of ‘asynchronous’ responses are represented as a function of the SOA difference between Trials $t-1$ and t (a positive difference corresponds to a larger SOA on Trial t than on Trial $t-1$, and reversed). Black circles represent trials where the order (i.e., the direction) of stimuli was identical in Trials $t-1$ and t , whereas white circles represent trials where the order was different. *SEMs* are shown as error bars

between Trials $t - 1$ and t , and order difference between $t - 1$ and t . On the x -axis, a negative value indicates that the SOAs corresponds to smaller SOAs on Trial t than on Trial $t - 1$ (the second stimulus appears earlier after the first one than on the previous trial), and reversed.

We conducted an ANOVA on the mean percentage asynchrony responses with SOA difference between Trials $t - 1$ and t ($-34/-51$, -17 , 0 , 17 , $34/51$ ms; we collapsed $34/51$ ms difference because the random distribution of SOAs across trials means that these differences occurred rarely), and order difference between Trials $t - 1$ and t (same order vs. different) as within-group variables. The ANOVA yielded a significant two-way interaction, $F(4, 52) = 7.8$, $p < .001$, partial $\eta^2 = 0.53$. Separate ANOVAs were conducted to further examine the interaction. The ANOVAs revealed a significant order effect when the SOA difference was $-34/-51$ ms, $F(1, 13) = 7.8$, $p < .05$, partial $\eta^2 = 0.37$; -17 ms, $F(1, 13) = 8.6$, $p < .05$, partial $\eta^2 = 0.4$; 0 ms, $F(1, 13) = 9.4$, $p < .01$, partial $\eta^2 = 0.42$; and 17 ms, $F(1, 13) = 21.3$, $p < .001$, partial $\eta^2 = 0.62$. The order effect was not significantly different when the SOA difference was $34/51$ ms ($F < 1$). The results indicate an advantage for same-order trials when the SOA was smaller on Trial t than on Trial $t - 1$, but an advantage for different-order trials when the SOA was longer or equal on Trial t as compared with Trial $t - 1$.

Comparison of the sequential effects for the various SOA differences

We wondered whether the advantage for different-order trials was related to an adaptation effect. This would correspond to a disadvantage for same-order trials, whereby the responsiveness to two asynchronous targets would decrease over time (i.e., from trial to trial) if they share the same physical (temporal and spatial) properties. If this were the case, then the advantage for different-order trials should be larger when the two consecutive trials share the same SOA than when they differ. To verify this possibility, we calculated the difference in performance between same-order and different-order trials for each SOA difference and compared them. The advantage for *different-order* trials was significantly smaller when SOAs were equal than when the difference was 17 ms, $F(1, 13) = 7.2$, $p < .05$, partial $\eta^2 = 0.36$, whereas there was no difference in the advantage for *same-order* trials when the SOA difference was -17 ms or $-34/51$ ms ($F < 1$, $p > .8$, partial $\eta^2 = 0.003$). These effects indicate that the advantage for different-order over same-order trials is not related to the similarity between successive trials in case of same-order trials.

Detection versus criterion

Thus far, the main result is the performance difference for same-order versus different-order trials when the SOA on Trial t is 17 ms longer than on Trial $t - 1$. One might wonder

whether this difference reflects a discrimination detection ability between same and different-order trials or a bias effect. For instance, participants could have been biased to respond ‘asynchronous’ in case of a mere suspicion of spatial order change between trials, and this bias could have been amplified when the SOA on the Trial t was slightly longer than on Trial $t - 1$. This should lead to increased bias when the SOA difference is 17 ms rather than, for example, 0 ms or -17 ms. We verified these possibilities by calculating d -prime (d') and criterion (c) corresponding to the performance difference between same-order and different-order trials, and did this for the different SOA differences. The percentage of ‘asynchronous’ responses for different-order trials was considered as hits, whereas the percentage of ‘asynchronous’ responses for same-order trials were considered as false alarms. Respectively, d' and c signify the discrimination ability (i.e., sensitivity) and response criteria. For a number of participants, performance was at ceiling when the SOA was larger than 30 ms on Trial t relative to Trial $t - 1$, making it impossible to use signal detection theory (Herzog, Francis, & Clarke, 2019). Therefore, we focused on performance for which there was no significant difference in mean performance (i.e., sequences with SOA differences of -17 , 0 , and 17 ms (there was respectively 67% , 71% , and 65% correct responses in these conditions), $F(2, 26) = 2.2$, ns , partial $\eta^2 = 0.15$).

Across SOA differences, d' differed significantly, $F(2, 26) = 17.4$, $p < .001$, partial $\eta^2 = 0.57$. The HSD Tukey post hoc analysis showed that the d' was significantly higher in the case of an SOA difference of 17 ms ($.33$) or 0 ms ($.16$) rather than -17 ms ($-.22$; $p < .001$ and $p < .005$ respectively). There was no significant difference for SOA differences of 17 and 0 ms. There was no significant difference in the analysis conducted on the criteria c , $F(2, 26) = 2.7$, $p = .08$, partial $\eta^2 = 0.17$. The results show an effect in terms of sensitivity (d'), but not in terms of the bias (c), indicating that the advantage for different-order trials at 17 ms is not related to a bias towards asynchronous responses when the SOA is longer on Trial t than on $t - 1$.

Sequential effects as a function of the response given on Trial $t - 1$

We examined the impact of the response given on Trial $t - 1$ by conducting an ANOVA on mean percentage of asynchronous responses, with SOA difference, order-difference between Trials $t - 1$ and Trial t (same vs. different), and the response on Trial $t - 1$ (‘simultaneous’ vs. ‘asynchronous’) as within-subject variables. We focused on the shortest SOA differences only (-17 , 0 , and 17 ms), as our previous analyses yielded significant differences for these conditions. Furthermore, these SOAs represented the vast majority of the trials. This analysis was conducted to examine whether the trial-to-trial effects observed depend on whether

participants perceived the preceding trial as synchronous or not (see Fig. 3).

The analysis showed that performance was better for trials preceded by a trial yielding an ‘asynchronous’ rather than a ‘simultaneous’ response, $F(1, 13) = 296, p < .001$, partial $\eta^2 = 0.96$. Most importantly, the analysis also showed a significant three-way interaction, $F(2, 26) = 5.3, p < .05$, partial $\eta^2 = 0.29$. The interaction was further examined by two separate ANOVAs. When the response on the previous trial was asynchronous, the two-way interaction between the SOA difference and the order difference failed to reach significance, $F(2, 26) = 1.2, ns$, partial $\eta^2 = 0.09$. The ANOVA yielded a significant interaction between the SOA difference and the order difference when participants perceived the previous trial as ‘synchronous,’ $F(2, 26) = 7.8, p < .005$, partial $\eta^2 = 0.37$. ANOVAs on each SOA difference showed a significant order effect when the SOA difference was 17 ms, $F(1, 13) = 19.1, p < .001$, partial $\eta^2 = 0.6$, but not for the other SOA differences (all $ps > .09$). The results indicate that the advantage for different-order trials does not require a subjective perception of asynchrony on Trial $t - 1$, as it was only observed when participants made a ‘simultaneous’ response on the preceding trial.

Response repetition effect

Finally, we examined whether subjects generally repeat their response from trial to trial, because it could explain the advantage for different-order over same-order trials—that is, more ‘simultaneous’ responses for same-order than for different-

order trials: This occurs when the subject answered ‘simultaneous’ on Trial $t - 1$, and subjects might repeat the ‘simultaneous’ response more when successive trials are identical (same-order trials) than when they differ (different-order trials). If this was the case, then participants should repeat their ‘simultaneous’ responses when the current SOA is 0 ms (trials with simultaneous stimuli had not been included in the previous analyses). We measured the rate of asynchronous responses at SOA 0 ms as a function of the response on the previous trial. However, rates of asynchronous responses were similar at SOA 0 ms when the response had been simultaneous on the previous trial (17.3%) or asynchronous on the previous trial (14.4%), $F(1, 13) < 1$, partial $\eta^2 = 0.017$. This shows that the subjective perception of simultaneity on Trial $t - 1$ does not bias the subjects to answer ‘simultaneous’ on Trial t , and is unlikely to explain the higher percentage of ‘simultaneous’ responses for same-order than for different-order trials.

Discussion

The results confirm that trial-to-trial effects do not correspond to a general order (direction) priming, or nonspecific adaptation. Effects depend on SOA differences between successive trials. When the SOA on Trial t is shorter than the SOA on Trial $t - 1$, asynchrony detection is improved on Trial t if the order of stimuli is similar on Trials $t - 1$ and t (on both trials the left target appeared first or on both trials the right target appeared first). In contrast, when the SOA on Trial t is 17 ms

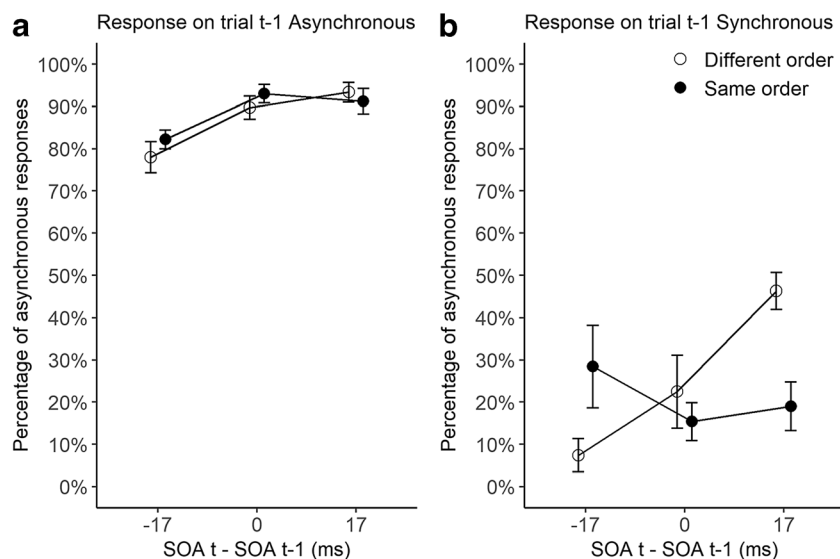


Fig. 3 Mean percentage of ‘asynchronous’ responses are shown as a function of the SOA difference between Trials $t - 1$ and t (a positive difference corresponds to a larger SOA on Trial t than on Trial $t - 1$, and reversed), when participants give an ‘asynchronous’ response on Trial $t - 1$ (a) and when they give a ‘synchronous’ response on Trial $t -$

1 (b). Black circles represent trials where the order (i.e., the direction) of stimuli was identical in Trials $t - 1$ and t , whereas the white circles represent trials where the order was different. *SEMs* are shown as error bars

longer than on Trial $t - 1$, asynchrony detection is better when the order (direction) is different on the successive trials. A similar but smaller effect is observed when SOAs are identical on Trial $t - 1$ and t . An advantage for different-order trials is mainly observed when the asynchrony is not reported on the preceding trial. The advantage for different-order trials is related to improved discrimination of different-order versus same-order trials, rather than a change in criterion.

Although the effects confirm our expectations, the argument for a displacement of the attention in space is indirect. In the following experiment, we investigate the importance of spatial location by comparing effects when the targets on Trials $t - 1$ and t are in the same versus in different locations.

Experiment 2

Experiment 2 was designed to examine whether the location of the targets plays a crucial role in the advantage for different-order as compared with same-order trials, as illustrated in Experiment 1, as it should be if this effect is related to attention shifts. In Experiment 2, the task was identical to Experiment 1, except that we manipulated the eccentricity of the targets, such that the eccentricity on the previous trial was the same (6°), or different (either smaller or larger; mean eccentricity was 6° on average), compared with the current trial. If the observed order effects are due to an anticipated shift of attention towards the *location* of the second target, then the effect should disappear when the target locations do not overlap from one trial to another. In other words, we expect to replicate the findings from Experiment 1 when the eccentricity on Trial t is similar to the eccentricity on Trial $t - 1$, but not when they are dissimilar.

Method

Experiment 2 was identical to Experiment 1, except for the following changes.

Participants

Nineteen students from the University of Strasbourg or members from the laboratory participated in Experiment 2. They were between the ages of 18 and 33 years ($M_{\text{age}} = 22.7$ years, $SD = 2.7$ years, 10 females, nine males). Experiment 2 was approved by a local ethics committee from the University of Strasbourg.

Equipment

The stimuli were generated using a DELL Dimension 4600 computer and a visual stimulus generator ViSaGe® (Visual Stimulus Generator, Cambridge Research Systems–CRS), and displayed on a 20-in. 120 Hz CRT screen (resolution

800×600). The experiments were developed using MATLAB software (R2007a) by The MathWorks and CRS VSG Toolbox for MATLAB. Two response buttons on the CRS CB6 Push Button Response Box were used for measuring the responses.

Stimuli

Target stimuli were two white target squares ($0.85^\circ \times 0.85^\circ$) displayed on the left and right of the screen centre, presented on a black background. The targets were displayed at three possible eccentricities: 2° , 6° , or 10° of visual angle from the centre of the screen (the distance was measured between the centre of the screen and the internal edge of the squares).

Procedure

Each trial began with the presentation of a central fixation point that stayed on the screen till the end of the ongoing trial (i.e., till the response of the subject). After a delay of 400 to 600 ms (the delay was jittered so that the stimuli could not be predicted in time relative to the fixation point), the left and the right target appeared across a range of SOAs (0, 17, 33, 50, 67, and 83 ms), so that participants were able to perform the simultaneity judgement (SJ) task. Subjects were instructed to press the left or right response key if they perceived the targets simultaneously or asynchronously, respectively. The display became blank after participants made their response, and the next trial was initiated after 2 seconds. The left or the right target could appear first with an equal probability. The eccentricity and SOAs were manipulated within blocks in random order. In total there were three blocks of 216 trials each.

Results

Note that only those trials were included in the analyses in which the eccentricity on Trial t was 6° (similar to Experiment 1), and the SOA difference from one trial to another was either -17 , 0 , and 17 ms (as these turned out to be the critical SOA differences in Experiment 1). The first trial for each block were discarded from further analyses. The results of Experiment 2 are shown in Fig. 4.

We conducted an ANOVA on the mean percentage of asynchronous responses with SOA differences between Trials $t - 1$ and t (-17 , 0 , 17 ms), order-difference between Trials $t - 1$ and t (same vs. different order), and eccentricity difference between Trials t and $t - 1$ (same vs. different) as within-subject variables. The ANOVA yielded a significant three-way interaction, $F(2, 36) = 6.4$, $p < .005$, partial $\eta^2 = 0.26$.

There was a significant two-way interaction between order difference and SOA difference when the eccentricity was identical between Trials t and $t - 1$, $F(2, 36) = 16.5$, $p < .001$, partial $\eta^2 = 0.48$. ANOVAs showed significant order

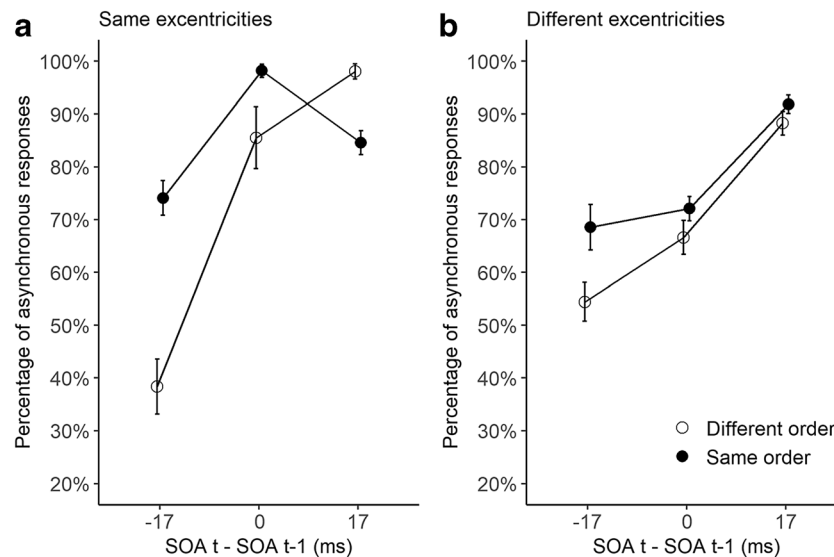


Fig. 4 Results of Experiment 2. Here, the mean percentage ‘asynchronous’ response is plotted as a function of the SOA difference between Trials t and $t - 1$ (a positive difference corresponds to a larger SOA on Trial t than on Trial $t - 1$). **a** Trials where the eccentricity was 6 degrees on both Trials t and $t - 1$. **b** Trials where the eccentricity was 6

degrees on Trial t , and either 2 or 10 degrees on Trial $t - 1$. Lines with filled black circles represent responses when the order (direction) of stimuli was identical in Trials $t - 1$ and t , whereas lines with white circles represent responses when the order of stimuli was different in Trials $t - 1$ and t . SEMs are shown as error bars

effects when the SOA difference was -17 ms, $F(1, 18) = 22$, $p < .001$, partial $\eta^2 = 0.55$; 0 ms, $F(1, 18) = 6.2$, $p < .05$, partial $\eta^2 = 0.25$; and 17 ms, $F(1, 18) = 23.9$, $p < .001$, partial $\eta^2 = 0.57$. The results indicate an advantage for same-order trials when the SOA was smaller or equal on Trial t and Trial $t - 1$, and an advantage for different-order trials selectively when the SOA was longer on Trial t as compared with Trial $t - 1$ (i.e., a replication of Experiment 1).

There was also a significant two-way interaction between order difference and SOA difference when the eccentricity was different between Trial t and $t - 1$, $F(2, 36) = 3.3$, $p < .05$, partial $\eta^2 = 0.15$. ANOVAs showed significant order effects only when the SOA difference was -17 ms, $F(1, 18) = 15.9$, $p < .001$, partial $\eta^2 = 0.47$. The results indicate an advantage for same-order trials when the SOA was smaller on Trial t than on Trial $t - 1$. Hence, contrary to conditions in which eccentricity remained the same, there was no advantage for different-order trials.

Detection versus criterion

Contrary to Experiment 1, the percentage of asynchronous responses was often at ceiling, and we declined to apply signal detection theory in Experiment 2.

Discussion

Experiment 2 replicated the advantage for different-order trials when the SOA on Trial t was 17 ms longer than on Trial $t - 1$. In line with Experiment 1, this effect was largest for this particular SOA difference. In fact, the effect was reversed for

an SOA difference of 0 ms or -17 ms. The advantage for same-order trials in case of an SOA difference of 0 ms confirms that the similarity of the consecutive trials is not the critical factor underlying the advantage for different-order trials observed at 17 ms. Moreover, the results show that the advantage for different-order trials is observed only when the targets are presented at the same location from Trial $t - 1$ to t . This location specific effect is consistent with the notion that attention is shifted towards the location of the second target on the preceding trial. In contrast, the advantage for same-order trials was significant regardless of the eccentricity on the preceding trial. This advantage may be due to a sense of motion direction (left–right or right–left).

In Experiments 1 and 2, the SOA difference between two successive trials was averaged over all SOAs on Trial t (except for the 0 -ms condition). Hence, it is unclear if the advantage for different-order versus same-order trials observed in Experiments 1 and 2 can occur even when SOAs themselves, and not only the SOA difference between consecutive trials, are subthreshold. Our hypothesis is that the trial-to-trial effects observed here reveal subconscious orientation of attention in time and space, which compensate for the relative sluggishness of voluntary attention moves. If this is the case, then attention shifts should be observed even for very brief asynchronies.

Experiment 3

In Experiment 3, our main aim was to investigate whether the observed trial-to-trial effects in Experiments 1 and 2 also

occur if the order of the targets on the current trial is too short to be perceived (i.e., subthreshold), because this would make it possible to shift attention in advance for sequences of events that follow one another very quickly, and hence to follow events fluently. In Experiment 3, the task was identical to the task in Experiments 1 and 2. However, Experiment 3 was divided into mini-blocks of four successive trials each. On the vast majority of trials (i.e., Trials 2–4 in the mini-blocks), the SOAs used were very brief (either 8 or 17 ms), such that we were able to investigate whether we can find evidence for order benefits using SOAs below threshold. In addition, the use of only two SOAs made it possible to easily balance all possible three trials sequences (trials 2–4), taking into account both SOA and spatial order of the three successive trials (see Procedure for details). To make sure that participants were presented clear-cut simultaneous and asynchronous stimuli, and were thus able to perform the task, the SOA of the first initial trial of each mini-block was either 0, 50, or 83 ms.

Because the aim of Experiment 3 was to explore sequential effects when the asynchronies are not detectable, we analyzed only the last two trials of each mini-block, as these trials were always preceded by two targets with a SOA of 8 or 17 ms. This was not the case for the second trial of each mini-block, as the initial SOA was either 0, 50 or 83 ms. In addition, we distinguished sequences starting with an initial SOA of 0, 50 or 83 ms. If sequential effects occur in an automatic fashion, then we expected to observe order benefits regardless of the sequence. In contrast, if they can occur for subthreshold asynchronies but require a minimum of effort, then the order benefits may disappear when the subjects are exposed to long series of trials with barely detectable asynchronies, especially after series starting with a synchronous trial. Only SOAs of 83 ms were expected to be detected without any effort in almost all trials.

Method

Experiment 3 was identical to the previous experiments, except for the following changes.

Participants

Seventeen participants were included in Experiment 3 ($M_{\text{age}} = 24.2$ years, $SD = 2.8$ years, 11 females, six males).

Equipment and stimuli

Stimuli were always displayed at 6° of visual angle from the centre of the screen.

Procedure

The delay between the fixation point and target display was jittered between 300 and 500 ms, so that the first stimulus could not be predicted in time. A total of 128 mini-blocks of four trials each were presented. For each mini-block, the SOA for the first trial was either 0, 50, or 83 ms. Each initial trial had a 25%, 37.5% and 37.5% probability to start with a 0, 50 and 83 ms SOA, respectively. The number of trials with 0-ms SOA was minimized in order to avoid a possible disengagement of the subjects, due to the difficulty to detect asynchronies. The SOA for the remaining three trials was either 8 or 17 ms.

We balanced the sequences of trials, and not only trials themselves like in the previous experiments. Because we look at sequential effects—that is, the processes occurring from Trial $t - 1$ to Trial t —it is important that the to-be-compared conditions are presented the same number of trials. Each possible sequence of three 8 and 17 ms SOA trials (eight possible SOA sequences \times eight possible spatial order sequences = 64 possibilities) was displayed twice across the experiment and presented in random order after the initial trial. The side of the response ('simultaneous' left and 'asynchronous' right, or the reverse) was counterbalanced between subjects.

Results

To make sure that the asynchrony on Trial $t - 1$ had not been perceived, we selected only those trials which yielded a 'simultaneous' response. Given the small SOAs used (8 and 17 ms), the vast majority of trials were perceived as synchronous (65.7%). The mean threshold for asynchrony detection was 34 ms. The results of Experiment 3 are shown in Fig. 5.

We conducted an ANOVA on the percentage of asynchronous responses, with the initial SOA (0, 50 and 83 ms), the SOA on Trial $t - 1$ (8 vs. 17 ms), the SOA on Trial t (8 vs. 17 ms) and the order-difference (same or different) as within-group variables. The three-way interaction between initial SOA, order difference, and SOA on Trial $t - 1$ was significant, $F(2, 32) = 3.7$, $p < .05$, partial $\eta^2 = 0.19$. The three-way interaction was further investigated by conducting an ANOVA, with order difference and SOA on $t - 1$ as within-subject variables for each initial SOA condition. When the initial SOA was 0 ms or 50 ms, the ANOVA yielded no significant two-way interaction ($F_s < 1$). Neither were the two main effects significant ($F_s < 1$). When the initial SOA was 83 ms, there was a significant interaction, $F(1, 16) = 13.9$, $p < .005$, partial $\eta^2 = 0.46$, between the SOA on Trial $t - 1$ (8 vs. 17 ms), and the order difference (same vs. different order on Trials $t - 1$ and t). ANOVAs were conducted for each SOA on Trial $t - 1$. When the SOA on Trial $t - 1$ was 8 ms (i.e., shorter or equal to the SOA on Trial t), there was a significant advantage for different-order over same-order trials, $F(1, 16)$

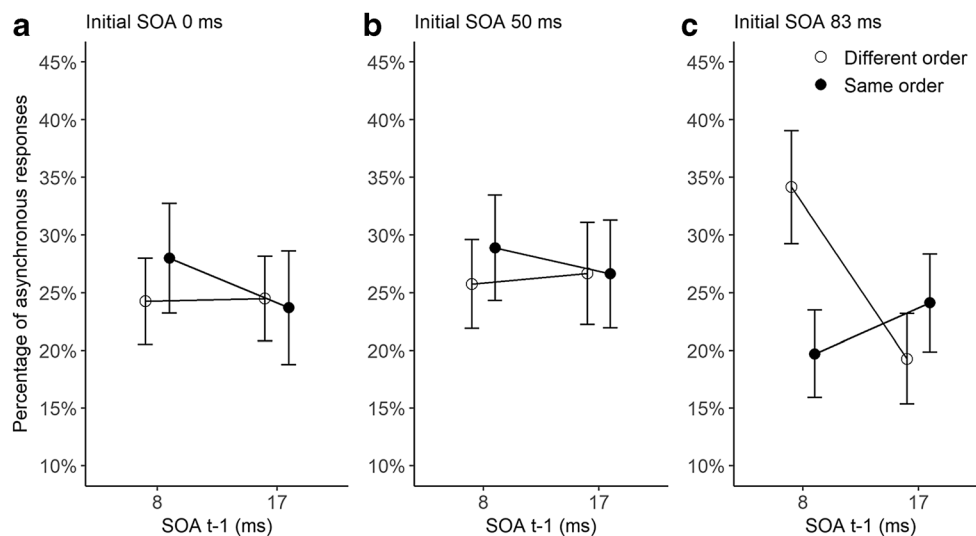


Fig 5 Percentage of ‘asynchronous’ responses (mean \pm SEM) after an initial trial with SOA of zero (**a**), 50 (**b**) or 83 ms (**c**), as a function of the relative order in Trials $t - 1$ and t (filled black circles: same order, vs. white circles: different order), and as a function of the SOA of the previous trial (SOA $t - 1$: 8 or 17 ms). The analysis was made on

performance following a ‘simultaneous’ response on Trial $t - 1$, to ensure that asynchronies on conditioning trials had not been consciously detected. The data are averaged over the SOA of the present trial (t ; i.e., either 8 or 17 ms)

$= 11.4, p < .005$, partial $\eta^2 = 0.42$. When the SOA on Trial $t - 1$ was 17 ms (i.e., longer or equal to the SOA on Trial t), there was no significant difference between same-order and different-order trials ($F < 1$). These results replicate those of Experiments 1 and 2, but only when the initial SOA is 83 ms.

We verified whether the advantage for different-order over same-order trials was due to an advantage for different-order trials or a disadvantage for same-order trials. We first compared the percentage of asynchrony responses for different-order trials after an SOA of 8 versus 17 ms on Trial $t - 1$ (initial SOA 83 ms). Asynchronous responses were more frequent after 8 ms (34%) than after 17 ms (19.3%), $F(1, 16) = 7.1, p < .05$, partial $\eta^2 = 0.31$. There was no difference in the percentage of asynchrony responses for same-order trials after an SOA of 8 versus 17 ms ($F < 1$). These results are consistent with an advantage for different-order trials rather than a disadvantage for same-order trials.

We investigated whether the advantage for different-order relative to same-order trials was related to a change in discrimination or bias by applying signal-detection theory, as in Experiment 1. The ANOVA conducted on the d' showed a significant interaction between the initial SOA (0 vs. 50 vs. 83 ms), and the SOA on Trial $t - 1$ (8 vs. 17 ms), $F(2, 32) = 6.1, p < .01$, partial $\eta^2 = 0.28$. The HSD Tukey post hoc test showed this to be due to a larger d' (0.75) when the initial SOA was 83 ms and the first SOA 8 ms, than when the initial SOA was 0 ms ($d' = -0.18, p < .05$). There was no other significant difference in the post hoc analysis, and no effect regarding the criterion c ($F_s < 1$).

We verified also the results when the response was ‘asynchronous’ on Trial $t - 1$. The percentage of ‘asynchronous’ responses was significantly higher when the order of the stimuli was identical on Trials $t - 1$ and t (46%) than when they differed (40%), as shown by a main effect of order difference, $F(1, 16) = 5.9, p < .05$, partial $\eta^2 = 0.27$. There were no other significant effects ($F_s < 2.2$).

Discussion

Results of Experiments 1 and 2 were replicated in Experiment 3, inasmuch as there was an advantage for same-order trials when the asynchrony was perceived on Trial $t - 1$, and an advantage for different-order trials when the asynchrony was not perceived, at least when the Trials $t - 1$ and t were preceded by a clear asynchrony (83 ms) two or three trials before. The latter suggests that the experience of an obvious asynchrony not too long before Trial t is a prerequisite for the sequential effects to occur when asynchronies are subthreshold. This suggests that trial-to-trial effects require involvement from the subject, and that they do not occur totally automatically.

Experiment 4

The advantage for different-order trials is reminiscent of the recalibration effect, albeit for a specific SOA difference. In order to dissociate the effect observed in the present data from a recalibration effect, we reused and analyzed a data set from

another study by Harvey et al. (2014). In their study, participants saw a green line at -45° and a red line at $+45^\circ$, which were displayed successively across a range of SOAs (see Fig. 6 for an illustration of an example trial), and participants were instructed to make a synchrony/asynchrony judgment (as in Experiments 1–3). Synchrony distributions were plotted as a function of the first target event on the preceding trial. Interestingly, and contrary to other studies using audiovisual stimuli (Van der Burg, Alais, & Cass, 2015), the point of subjective simultaneity was not contingent upon the order of the targets on the preceding trial, indicating the absence of a visual temporal recalibration effect. With regard to the present study, if the intertrial effects observed in Experiments 1 to 3 are similar to a recalibration effect, we should find no trial-to-trial effect in Experiment 4, as Harvey and colleagues illustrated that the preceding order did not shift the synchrony distribution. If, in contrast, we find an advantage for different-order trials, this would represent an argument for a dissociation between this advantage and a recalibration effect.

In addition, Experiment 4 allows us to verify the role of motion direction coding. Effects observed in Experiments 1–3 varied as a function of time *and* space. Furthermore, Experiment 2 confirmed the importance of spatial overlap between successive trials. It is therefore questionable whether the observed sequential effects are due to participants making a temporal judgment or a motion judgment (or a combination of both; Cass & Van der Burg, 2014, 2019). Experiment 4 enables us to examine whether sequential effects can be found with a different stimulus setting that is unlikely to elicit a sense of motion direction. In the Harvey et al. (2014) study, the stimuli were spatially overlapping and therefore less likely to

elicit a motion direction. If the results observed in Experiments 1–3 are independent of a motion direction, then we expect to replicate Experiments 1–3.

Method

We summarize here the characteristics of the experiment. More details can be found in Harvey et al. (2014).

Participants

Fourteen healthy volunteers had participated in Harvey et al.'s (2014) experiment ($M_{\text{age}} = 21.3$ years, eight females, six males). All had normal or corrected-to-normal visual acuity. The project was approved by the Human Research Ethics Committee of the University of Sydney.

Equipment

The stimuli were generated using E-Prime 2.0 software on a Dell Optiplex 990, Intel i7-2600 CPU at 3.40 GHz (with 8 GB of RAM and an AMD Radeon HD 6350 graphics card running Windows 7 Enterprise 32 bit) and displayed on a Sony Trinitron CPD-E400 CRT 22-in. monitor 57 cm from the observer, at a refresh rate of 75 Hz (resolution $1,280 \times 1,024$). Manual responses were recorded using a Dell wired USB keyboard.

Stimuli

The stimuli were a red line at $+45^\circ$ and a green line at -45° crossing at the centre of the screen. The intersection was

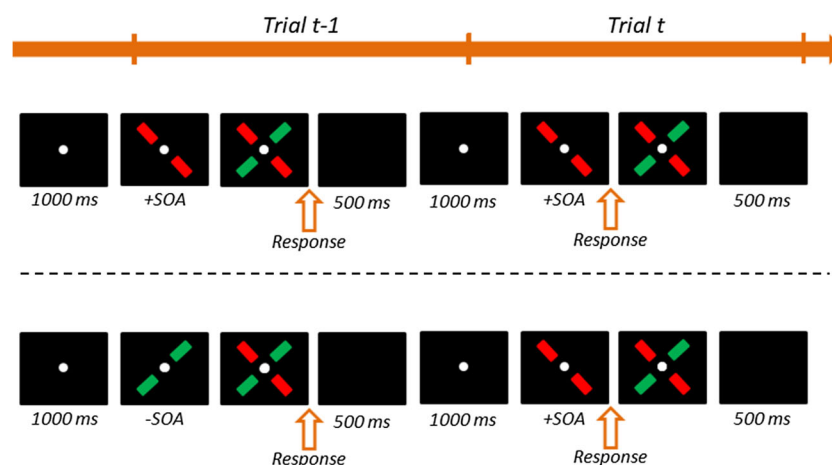


Fig. 6 Stimuli used in Experiment 4: a red line at $+45^\circ$ and a green line at -45° , partially covered by a grey fixation point. The presentation of the fixation point indicated the beginning of the trial. The stimuli were then displayed, separated by a given SOA. Note that the sign of the SOA represents the order in which the two stimuli appear. Participants made a response indicating whether they perceived the stimuli as simultaneous

or asynchronous. The next trial began after a delay of 500 ms. The upper section of the figure shows a sequence of trials where the red stimulus appears before the green stimulus (positive SOAs). The bottom section shows a sequence of trials where the sign of the SOAs differ: the green stimulus appears first on Trial $t - 1$ (negative SOA) and the red stimulus appears first on Trial t (positive SOA). (Color figure online)

covered by a grey fixation point (0.4° in diameter), leaving four segments visible (a pair of red ones at $+45^\circ$ and a pair of green ones at -45°), each measuring 0.7° in length. The red and green lines were separated by an SOA drawn randomly from a range of SOAs (0, ± 6 , ± 14 , ± 50 , ± 200 , ± 400 ms). The sign of the SOAs indicate the order in which the stimuli appeared on a given trial: negative SOAs correspond to the green line appearing first, and positive SOAs correspond to the red line appearing first.

Procedure

As shown in Fig. 6, each trial began with the presentation of a central fixation point. After a delay of 1,000 ms, the red and green lines were displayed with an SOA drawn randomly from the range of SOAs specified above. The stimuli stayed on the screen until subjects had responded. Subjects performed a simultaneity/asynchrony judgment task, where they had to press one response key in case they perceived the stimuli as simultaneous and another key in case they perceived them as asynchronous. After the response, there was a blank screen for 500 ms before the next trial was initiated. Participants completed four blocks of 144 trials, and the SOAs were randomized within blocks. Each block took approximately 20 min to complete and was followed by a break. Before the experiment, participants carried out practice trials in order to familiarize themselves with the task.

In the Experiment designed by Harvey et al. (2014), performance reached a plateau at an SOA of 50 ms and could hardly be expected to be modulated. For this reason, we focused on the effects observed for SOAs of 6 and 14 ms. We also restricted our analysis on sequences of trials where the two subsequent SOAs were identical because these were the only conditions with enough trials. The results of Experiment 4 are shown in Fig. 7.

An ANOVA was conducted on the mean percentage of asynchronous responses with response to Trial $t - 1$ (simultaneous vs. asynchronous) and the relative feature order of trials (same vs. different on Trials $t - 1$ and t) as within-group variables.

The ANOVA yielded a significant main effect of response on Trial $t - 1$, $F(1, 13) = 144.7$, $p < .001$, partial $\eta^2 = 0.92$. The rate of correct responses was higher by 42% when stimuli on Trial $t - 1$ were judged asynchronous (59%) than when they were judged simultaneous (17%). The results also showed a significant two-way interaction, $F(1, 13) = 5.4$, $p < .05$, partial $\eta^2 = 0.29$. The interaction was further examined using two one-way ANOVAs for each response type on the preceding trial. When participants made a ‘synchronous’ response on the preceding trial, the ANOVA revealed the responses were more accurate by 13% when the stimulus order between successive trials was different (23.4%) than when it was the same (10.8%), $F(1, 13) = 5.9$, $p < .05$, partial $\eta^2 = 0.31$. When the

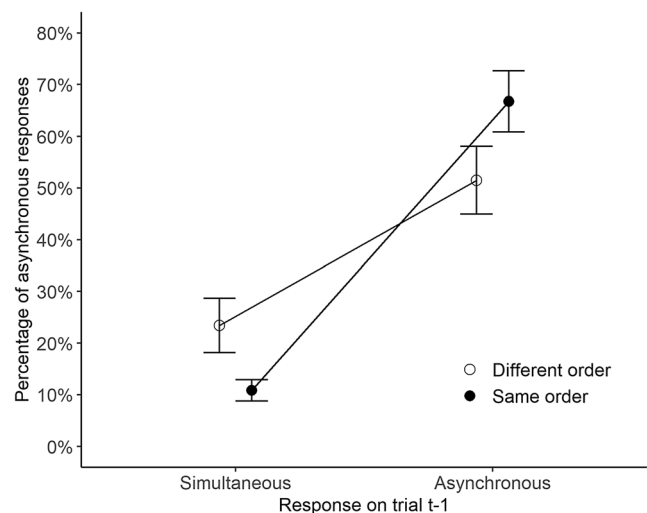


Fig. 7 Rate of correct ‘asynchronous’ responses (mean \pm SEM), as a function of the response on Trial $t - 1$ (simultaneous vs. asynchronous), and the relative order of Trials $t - 1$ versus t (identical with black circles and different with white circles). The analysis was performed on SOAs of 6 and 14 ms

stimuli were judged as asynchronous on Trial $t - 1$, no such effect was found, $F(1, 13) = 2.7$, $p = .13$, partial $\eta^2 = 0.17$.

Discussion

Like in Experiments 1 and 2, there was an advantage for different-order trials when the asynchrony was not perceived on Trial $t - 1$, suggesting a dissociation between this advantage and recalibration effects. Unlike in Experiments 1–3, however, in Experiment 4 stimuli were overlapping in space and could not elicit a sense of direction. Hence, the results suggest that the advantage for different-order trials is independent of the perception of motion direction.

General discussion

In the present study, we investigated whether temporal and spatial information about visual sequences influences when and where we look subsequently. In four experiments, we show an advantage for different-order trials (Experiments 1–4)—that is, improved asynchrony detection on Trial t when stimuli are displayed in a different order compared with the order on the preceding trial ($t - 1$). However, this improvement was predominantly observed when subjects failed to detect an asynchrony on the previous trial. Furthermore, this advantage for different-order trials depends on the relative SOA between the two successive trials (Experiments 1–3). More specifically, the largest effects were observed when the SOA on Trial t was 17 ms larger than on Trial $t - 1$ (Experiments 1 and 2). The advantage for different-order trials disappeared when the location of the targets differed from the

trial before (Experiment 2). Finally, the advantage for different-order trials was still observed in a data set without recalibration effect (Experiment 4), suggesting a dissociation between the advantage for different-order trials as observed in Experiments 1–4 versus temporal recalibration. It is to be noted that the advantage for different-order trials was replicated across experiments, which were each programmed with different randomization tools. In Experiment 3, trial sequences were precisely balanced, making it unlikely that serial dependency explains the results.

These results are consistent with our notion that subjects shift their attention in time and space, according to the events on the previous trial. Attention is shifted to the location of the previous second target, and performance improves if the first target appears in this location (i.e., a different-order trial), and if the second target occurs later after the first target than in the previous trial. In that case only, attention lands on a target when it is still alone on the screen (see Fig. 1). This explains why performance improves for different-order trials only when the SOA in Trial t is larger than on Trial $t - 1$.

In addition to the advantage for different-order over same-order trials, we also observed an improvement when the order of the events on a given trial was similar to the order on the previous trial. Such an improvement was observed when the SOA on Trial $t - 1$ was longer than the SOA on Trial t (Experiments 1 and 2), and contrary to the different order effect, this improvement was mainly observed when the asynchrony between two targets was perceived on the previous trial (Experiment 2).

As a whole, the pattern of results allows us to discuss different alternative explanations. The impact of the response on Trial $t - 1$ suggests that the facilitation for same-order trials depends on the detectability of the asynchrony on Trial $t - 1$. This might be akin to a priming effect, and especially a priming of direction. A role for direction priming is also supported by the fact that the advantage for same-order trials remains even when the eccentricity of targets changes between trials (Experiment 2). Direction indeed stays the same whatever the eccentricity of the targets, and direction priming is not expected to be sensitive to the location of the targets. It is thus clear that direction is processed, at least in Experiment 1–3.

Whereas direction priming may be an explanation for the same-order effects, it is questionable whether this can also explain the improved performance for different-order trials. A priming of subthreshold direction has been demonstrated in the literature (Melcher & Morrone, 2003), and shorter presentations of motion stimuli often favor priming effects (Brascamp, Knapen, Kanai, van Ee, & van den Berg, 2007; Kanai & Verstraten, 2005; Lauffs, Choung, Öğmen, & Herzog, 2018; Pinkus & Pantle, 1997; but see Alais, Leung, & Van der Burg, 2017). Priming per se cannot explain the advantage for different-order trials, because the results are opposite to a priming effect.

Adaptation has also been repeatedly shown, though, and especially motion adaptation. If exposure to a given motion direction is long enough, it causes a reduction of the response to this precise direction (Kohn & Movshon, 2004; Petersen, Baker, & Allman, 1985). Adaptation would best fit with an advantage for different-order trials. However, several results allow us to discard this explanation. First it is not clear why the advantage for different-order trials should occur only if the SOA on Trial t is 17 ms longer or equal to Trial $t - 1$. Moreover, adaptation to direction should not depend on the precise location of the stimuli, and should have persisted whatever the eccentricity of the targets in Experiment 2. This was not the case. Finally, in Experiment 4, we investigated sequential effects when stimuli could not elicit a sense of motion direction. Despite this, the advantage for different-order trials was still observed. All in all, the results suggest that the mechanisms at work for same-order and different-order trials differ, and that the processing of motion direction does not explain the advantage for different-order trials.

A global recalibration effect did not occur (i.e., a general advantage for different-order trials). The advantage for different-order trials seems to be very specific to short SOA differences between the two successive trials (Experiments 1–3). This result is consistent with a previous study (Harvey et al., 2014), which showed no global shift of threshold in case of unisensory information. The contrast between a global adaptation effect and the performance modulation described in the present study is confirmed in Experiment 4. We used the same data as in Harvey et al.'s (2014) study, in which it had been shown that with unisensory information, there is no temporal recalibration of threshold on a trial-to-trial basis. Despite this, performance improved in case of different-order trials, as compared with same-order trials, when SOAs below 50 ms were identical on the successive trials. These results show that the advantage observed for different-order trials is different from temporal recalibration. Furthermore, recent studies reported that rapid temporal recalibration to audiovisual asynchronies were independent on whether participants perceive the preceding trial as being synchronous or asynchronous (Van der Burg et al., 2013; Van der Burg & Goodbourn, 2015). This is clearly different from the present results, where we showed that the advantage for different-order trials was observed mainly when the asynchrony was *not* perceived on Trial $t - 1$, and specifically when the SOA on Trial $t - 1$ (the previous trial) was slightly shorter or equal to the SOA on Trial t (the present trial). Taken together, the results suggest the existence of mechanisms that differ from the trial-to-trial effects described in the literature. This makes sense inasmuch as recalibration may reflect an adaptation in order to better bind information from different sources, whereas the advantage for different-order trials described in the present work would be the consequence of our ability to predict and follow information from the same source at a high frequency rate.

In Experiments 1–4, we observed an advantage for different-order versus same-order trials. One might argue that subjects tend to repeat the response given on Trial $t - 1$ if the stimulus is similar on the two successive trials, and alternate responses if the stimuli are different. This might explain an advantage for different-order over same-order trials when the response on Trial $t - 1$ is ‘simultaneous’. However, if this was the case, then a response repetition effect would still not explain why the improvement was only observed for certain SOA differences. For instance, in Experiment 3, the advantage for different-order trials was observed when the SOA on Trial $t - 1$ was 8 ms, but not when it was 17 ms. Moreover, no response repetition was observed in Experiment 1 when the SOA on Trial t was 0 ms. Furthermore, applying signal detection theory in Experiments 1 and 3 supports the notion that the observed improvements for different-order versus same-order trials are related to a change in discrimination sensitivity rather than decision criterion.

The advantage for different-order trials rather fits with an attention shift and with previous studies (Lalanne, Van Assche, & Giersch, 2012; Lalanne, Lalanne, Van Assche, & Giersch, 2012; Poncelet & Giersch, 2015). Importantly, Experiment 4 suggests that this attention shift is not necessarily spatial. To summarize our interpretation, it was expected that the trial-to-trial prediction would include the location (or the features) of the last stimulus at around the same time after the first stimulus as on the previous trial. Such an orientation of attention may explain the advantage for different-order trials (or different feature-order trials) when the second stimulus appears later than expected (Experiments 1–3) or at the expected time (i.e. when the SOAs on Trials t and $t - 1$ are identical; Experiment 1, 3, 4). As mentioned in the introduction, attention would be shifted towards the location (or the feature) of the first stimulus of Trial t in case of different-order trials—that is, when the first target of Trial t is presented at the same location (or the feature) of the second target on Trial $t - 1$. If participants attend to the first stimulus when it is still alone on the screen, then subjects might be better able to detect the asynchrony. The fact that this effect works even when SOAs are identical on the two successive trials can be explained by attention being shifted slightly in advance, so that the first stimulus is still detected as isolated on the screen. In contrast, when the order of the stimuli is identical from trial to trial, subjects may miss the first stimulus and the asynchrony between the two stimuli because their attention is directed towards the second stimulus. This should impair asynchrony detection when stimulus order is the same on Trials $t - 1$ and t . Both effects may explain the advantage for different-order trials when the SOA of Trial $t - 1$ is smaller than the SOA on Trial t . Most importantly, it is easy to explain why the advantage for different-order trials disappears if the SOA on Trial t is larger than on Trial $t - 1$ by more than 17 ms. In that case, there is no need to attend to the first target, as the delay is

long enough to perceive the asynchrony between the two visual targets. In sum, the hypothesis of an attention shift helps to understand the SOA specificity of the advantage for different-order trials.

Our explanation is thus mainly in terms of attention shift, which might suggest a cognitive effect. However, the attention shift, as seen in Experiment 3, is observed when subjects are not aware of the asynchrony between the two events (see also Poncelet & Giersch, 2015). Unconscious shifts of attention have been reported in the literature before (Kendridge, Nijboer, & Heywood, 2008; Wyart & Tallon-Baudry, 2008). In fact, the displacement of attention to the location (feature) of the second square of the previous trial ($t - 1$) appears to be what is left when there is no conscious perception of direction or feature order on Trial $t - 1$. Such unconscious attention shifts may help to anticipate and follow sequences of visual events with a high temporal accuracy, like complex gestures or facial mimics. It might be surprising at first sight that such a high temporal accuracy prediction does not entail a prediction of direction. However, if one considers that what is encoded here is not the trajectory of one single stimulus but rather the sequence of distinct stimuli onsets, then there is no reason why a direction should be coded between distinct stimuli. What would be retained is rather the location and the features of the last visual stimulus (i.e., the location and features of the end of the sequence).

It should be noted that the retention of the location of the last stimulus of Trial $t - 1$ does not mean that the attention of the subject lingers on the last stimulus of the sequence once the sequence is over. If this had been the case, then the advantage for different-order trials should have occurred whatever the SOAs of the successive trials, because the attention of the subjects would have been located on the first stimulus of Trial t even when the SOA of Trial t was shorter than of Trial $t - 1$. No advantage for different-order trials was observed in that case, however. This supports the hypothesis that attention is shifted precisely in time and space once it is triggered by a signal (the first stimulus), indicating the beginning of a sequence.

Finally, even though the attention shift appears to occur for subthreshold SOAs, it does not occur systematically. In Experiment 3, it disappears after sequences of trials with only short asynchronies and without clearly visible asynchronies, and even after 50 ms asynchronies. It reappears only after obvious 83-ms asynchronies. The fact that the advantage for different-order trials appears only in that case suggests that predicting a sequence of sensory information and shifting attention requires task involvement from the subject.

Taken together, expectations based on past experiences may guide attention in time and space, such that they influence the perception of subsequent events. The anticipation of the points in time at which important information can be expected may help to follow sequences of visual events that unfold with high

temporal frequency. In turn, this may also help to imitate sequences of actions, especially those that involve complex sequences of coordinated actions between hands, arms, and legs.

Acknowledgements We thank INSERM, the University Hospital of Strasbourg and of Lyon (Le Vinatier), which provided logistical support for this research. Experiment 1 was supported by a grant from the Conseil Scientifique de la recherche de l'Hôpital le Vinatier (CSR F05, AO2014) and Experiment 2 by an ANR grant (Autotime, ANR-16-CE37-0004), which also supported the second author, P.P. The first author (E.M.C.) was supported by FRM (Fondation pour la Recherche Médicale, DPP20151033957 FRM R16029MM), FondaMental, and the FHU (Fédération Hospitalo-Universitaire) NeurogenYcs. We also thank Ljubica Jovanovic for her careful reading of the manuscript, and Lucie Rausch for helping collecting the data of Experiment 2.

Data availability statement The data sets generated during or analyzed during the current study are available from the corresponding author upon reasonable request.

References

- Alais, D., Leung, J., & Van der Burg, E. (2017). Linear Summation of Repulsive and Attractive Serial Dependencies: Orientation and Motion Dependencies Sum in Motion Perception. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 37(16), 4381–4390. <https://doi.org/10.1523/JNEUROSCI.4601-15.2017>
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436
- Brascamp, J. W., Knapen, T. H. J., Kanai, R., van Ee, R., & van den Berg, A. V. (2007). Flash suppression and flash facilitation in binocular rivalry. *Journal of Vision*, 7(12), 12.1–12. doi:<https://doi.org/10.1167/7.12.12>
- Cass, J., & Van der Burg, E. (2014). Remote temporal camouflage: Contextual flicker disrupts perceived visual temporal order. *Vision Research*, 103, 92–100. doi:<https://doi.org/10.1016/j.visres.2014.08.008>
- Cass, J., & Van der Burg, E. (2019). Dynamic distractor environments reveal classic visual field anisotropies for judgments of temporal order. *Attention, Perception, & Psychophysics*, 81(3), 738–751. doi:<https://doi.org/10.3758/s13414-018-1628-2>
- Dainton, B. (2017). Temporal consciousness. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Fall 2017 ed.). Retrieved from <https://plato.stanford.edu/archives/fall2017/entries/consciousness-temporal/>
- Deubel, H. (2008). The time course of presaccadic attention shifts. *Psychological Research*, 72(6), 630–640. doi:<https://doi.org/10.1007/s00426-008-0165-3>
- Elliott, M. A., & Giersch, A. (2016). What happens in a moment. *Frontiers in Psychology*, 6, 1905. doi:<https://doi.org/10.3389/fpsyg.2015.01905>
- Fiebelkorn, I. C., Pinsk, M. A., & Kastner, S. (2018). A dynamic interplay within the frontoparietal network underlies rhythmic spatial attention. *Neuron*, 99(4), 842–853.e8. doi:<https://doi.org/10.1016/j.neuron.2018.07.038>
- Giersch, A., Lalanne, L., Corves, C., Seubert, J., Shi, Z., Foucher, J., & Elliott, M. A. (2009). Extended visual simultaneity thresholds in patients with schizophrenia. *Schizophrenia Bulletin*, 35(4), 816–825. doi:<https://doi.org/10.1093/schbul/sbn016>
- Giersch, A., Poncelet, P., Capa, R. L., Martin, B., Duval, C. Z., Curziotti, M., . . . Lalanne, L. (2015). Disruption of information processing in schizophrenia: The time perspective. *Schizophrenia Research: Cognition*, 2, 78–83. doi:<https://doi.org/10.1016/j.scog.2015.04.002>
- Harvey, C., Van der Burg, E., & Alais, D. (2014). Rapid temporal recalibration occurs crossmodally without stimulus specificity but is absent unimodally. *Brain Research*, 1585, 120–130. doi:<https://doi.org/10.1016/j.brainres.2014.08.028>
- Helfrich, R. F., Fiebelkorn, I. C., Szczepanski, S. M., Lin, J. J., Parvizi, J., Knight, R. T., & Kastner, S. (2018). Neural mechanisms of sustained attention are rhythmic. *Neuron*, 99(4), 854–865, e5. doi:<https://doi.org/10.1016/j.neuron.2018.07.032>
- Herzog, M. H., Francis, G., & Clarke, A. (2019). *Understanding statistics and experimental design*. Cham, Switzerland: Springer.
- Herzog, M. H., Kammer, T., & Scharnowski, F. (2016). Time slices: What is the duration of a percept? *PLoS Biology*, 14(4), e1002433. doi:<https://doi.org/10.1371/journal.pbio.1002433>
- Kanai, R., & Verstraten, F. A. J. (2005). Perceptual manifestations of fast neural plasticity: Motion priming, rapid motion aftereffect and perceptual sensitization. *Vision Research*, 45(2526), 3109–3116. doi:<https://doi.org/10.1016/j.visres.2005.05.014>
- Kang, H., Lancelin, D., & Pressnitzer, D. (2018). Memory for random time patterns in audition, touch, and vision. *Neuroscience*, 389, 118–132. doi:<https://doi.org/10.1016/j.neuroscience.2018.03.017>
- Kentridge, R. W., Nijboer, T. C. W., & Heywood, C. A. (2008). Attended but unseen: Visual attention is not sufficient for visual awareness. *Neuropsychologia*, 46(3), 864–869. doi:<https://doi.org/10.1016/j.neuropsychologia.2007.11.036>
- Kohn, A., & Movshon, J. A. (2004). Adaptation changes the direction tuning of macaque MT neurons. *Nature Neuroscience*, 7, 764–772.
- Lalanne, L., Van Assche, M., & Giersch, A. (2012). When predictive mechanisms go wrong: Disordered visual synchrony thresholds in schizophrenia. *Schizophrenia Bulletin*, 38(3), 506–513. doi:<https://doi.org/10.1093/schbul/sbq107>
- Lalanne, L., Van Assche, M., Wang, W., & Giersch, A. (2012). Looking forward: An impaired ability in patients with schizophrenia? *Neuropsychologia*, 50(12), 2736–2744. doi:<https://doi.org/10.1016/j.neuropsychologia.2012.07.023>
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, 106(1), 119–159.
- Lauffs, M. M., Choung, O.-H., Ögmen, H., & Herzog, M. H. (2018). Unconscious retinotopic motion processing affects non-retinotopic motion perception. *Consciousness and Cognition*, 62, 135–147. doi:<https://doi.org/10.1016/j.concog.2018.03.007>
- Los, S. A., Kruijine, W., & Meeter, M. (2014). Outlines of a multiple trace theory of temporal preparation. *Frontiers in Psychology*, 5, 1058. <https://doi.org/10.3389/fpsyg.2014.01058>
- Los, S. A., Kruijine, W., & Meeter, M. (2017). Hazard versus history: Temporal preparation is driven by past experience. *Journal of Experimental Psychology: Human Perception and Performance*, 43(1), 78–88. doi:<https://doi.org/10.1037/xhp0000279>
- Los, S. A., & van den Heuvel, C. E. (2001). Intentional and unintentional contributions to nonspecific preparation during reaction time foreperiods. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2), 370–386.
- Melcher, D., & Morrone, M. C. (2003). Spatiotopic temporal integration of visual motion across saccadic eye movements. *Nature Neuroscience*, 6(8), 877–881. doi:<https://doi.org/10.1038/nn1098>
- Niemi, P., & Näätänen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin*, 89(1), 133–162. doi:<https://doi.org/10.1037/0033-2909.89.1.133>
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10(4), 437–442.
- Petersen, S. E., Baker, J. F., & Allman, J. M. (1985). Direction specific adaptation in area MT of the owl monkey. *Brain Research*, 346, 146–150.

- Pinkus, A., & Pantle, A. (1997). Probing visual motion signals with a priming paradigm. *Vision Research*, 37(5), 541–552.
- Poncelet, P. E., & Giersch, A. (2015). Tracking visual events in time in the absence of time perception: Implicit processing at the ms level. *PLoS One*, 10(6), e0127106. doi:<https://doi.org/10.1371/journal.pone.0127106>
- Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: a review of recent research (2006–2012). *Psychonomic Bulletin & Review*, 20(3), 403–452. doi:<https://doi.org/10.3758/s13423-012-0371-2>
- Scharnowski, F., Rüter, J., Jolij, J., Hermens, F., Kammer, T., & Herzog, M. H. (2009). Long-lasting modulation of feature integration by transcranial magnetic stimulation. *Journal of Vision*, 9(6), 1.1–10. doi:<https://doi.org/10.1167/9.6.1>
- Steinbohm, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2008). Sequential effects within a short foreperiod context: Evidence for the conditioning account of temporal preparation. *Acta Psychologica*, 129(2), 297–307. doi:<https://doi.org/10.1016/j.actpsy.2008.08.005>
- Su, Y.-H., & Salazar-López, E. (2016). Visual timing of structured dance movements resembles auditory rhythm perception. *Neural Plasticity*, 2016, 1678390. doi:<https://doi.org/10.1155/2016/1678390>
- Vallesi, A., Lozano, V. N., & Correa, Á. (2013). Dissociating temporal preparation processes as a function of the inter-trial interval duration. *Cognition*, 127(1), 22–30. doi:<https://doi.org/10.1016/j.cognition.2012.11.011>
- Van der Burg, E., Alais, D., & Cass, J. (2013). Rapid recalibration to audiovisual asynchrony. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 33(37), 14633–14637. doi:<https://doi.org/10.1523/JNEUROSCI.1182-13.2013>
- Van der Burg, E., Alais, D., & Cass, J. (2015). Audiovisual temporal recalibration occurs independently at two different time scales. *Scientific Reports*, 5, 14526. doi:<https://doi.org/10.1038/srep14526>
- Van der Burg, E., Alais, D., & Cass, J. (2018). Rapid recalibration to audiovisual asynchrony follows the physical-not the perceived-temporal order. *Attention, Perception, & Psychophysics*, 80(8), 2060–2068. doi:<https://doi.org/10.3758/s13414-018-1540-9>
- Van der Burg, E., & Goodbourn, P. T. (2015). Rapid, generalized adaptation to asynchronous audiovisual speech. *Proceedings of the Biological Sciences*, 282(1804), 20143083. doi:<https://doi.org/10.1098/rspb.2014.3083>
- Van Rullen, R. (2018). Attention cycles. *Neuron*, 99(4), 632–634. doi:<https://doi.org/10.1016/j.neuron.2018.08.006>
- van Wassenhove, V. (2009). Minding time in an amodal representational space. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 364(1525), 1815–1830. doi:<https://doi.org/10.1098/rstb.2009.0023>
- Wyart, V., & Tallon-Baudry, C. (2008). Neural dissociation between visual awareness and spatial attention. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 28(10), 2667–2679. doi:<https://doi.org/10.1523/JNEUROSCI.4748-07.2008>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.