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Title : Evidence for visual temporal order processing below the threshold for conscious perception

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Key words : Temporal order, subconscious, visual, timing, attention, simultaneity

Abstract

Correctly discriminating the order of events arising in our environment is a fundamental temporal process that allows us to better understand and interact with our dynamic world. However, if consecutive events are separated by an interval of less than 20-40ms, we cannot consciously perceive their relative order. Nevertheless, indirect evidence suggests that the sequential order of events separated by less than 20ms might still be processed subconsciously. In our study, we aimed to provide evidence that temporal order processing can occur below the threshold for conscious perception. We developed a novel paradigm in which participants were instructed that a visual cue, composed of two coloured stimuli appearing in a particular order, would allow them to predict the shape of a subsequent target. The interval between the two stimuli allowed temporal order to be consciously perceived (66ms interval) or not (17ms interval), as verified by performance on a separate temporal order judgement task. Performance was compared to a control condition that provided no predictive information. In both experiments, reaction times were faster in the order-cue conditions compared to the control condition, whether the SOA separating events was longer (66ms) or shorter (17ms) than the typical temporal order threshold. Therefore, even when participants could not consciously perceive the temporal order of two consecutive stimuli, the relative sequence of events was nevertheless processed and used to optimise performance. These results suggest that temporal order can be processed subconsciously.

Key words : Temporal order; subconscious; visual; timing; attention; simultaneity

1.Introduction

The ability to correctly parse and perceive the order of events in time is a fundamental aspect of our subjective experience. For example, our ability to understand a sentence, perceive a melody or watch a movie and understand the story requires us to process the order of the information (words, musical notes or images) presented to us. Moreover, the perception of temporal order is known to be impaired in several clinical disorders, such as schizophrenia (Capa et al., 2014; Schwartz et al., 1991) or dyslexia (Farmer & Klein, 1995; Jaśkowski & Rusiak, 2008; Ortiz et al., 2014).

A classic paradigm for studying the processing of temporal order is the temporal order judgment (TOJ) task, which consists of presenting two consecutive stimuli separated by a very brief delay (the "stimulus onset asynchrony" (SOA)) and asking participants which of the two stimuli appeared first. Many studies demonstrate that the temporal order of two stimuli can be perceived at an inter-stimulus interval of at least 20-40ms (Hirsh, 1959; Hirsh & Sherrick Jr, 1961; Kanabus et al., 2002; Pastore & Farrington, 1996; Pöppel, 1997), known as the temporal order threshold. Intriguingly, even though the auditory system has better temporal resolution than the visual one (Wittmann, 1999, 2011), the temporal order threshold is similar across visual, auditory and tactile modalities (Hirsh & Sherrick Jr, 1961; Kanabus et al., 2002; Wittmann, 1999, 2011).

Pöppel (1997) provides a theory to explain the neural basis of temporal order perception. In this model, the brain divides up the continuous information flow provided by different sensory modalities into "temporal system states". These temporal system states are proposed to be implemented by neural oscillations (Pöppel, 1970) with the period of one oscillation (e.g. 30ms) corresponding to one system state. This processing unit allows events to be distinguished within the flow of information. However, if several events occur within one temporal system state then these events are treated as co-temporal, therefore explaining why the temporal order of two stimuli separated by less than 20-40ms can't be perceived. Importantly, neurophysiological data provide support for this idea (Cecere et al., 2015; Milton & Pleydell-Pearce, 2016; VanRullen, 2016; Varela et al., 1981). For example, the lower the frequency of neural oscillations in the alpha band (8-12Hz), the more likely it is that two consecutive events will be integrated. By contrast, the higher the alpha frequency, the more likely they are to be segregated (Samaha & Postle, 2015; Wutz et al., 2018).

Nevertheless, just because events occur at intervals shorter than the temporal order threshold doesn't mean that the brain cannot process the temporal order information they convey or, at the very least, process that information in a sequential order. Indeed, there is an important distinction between the ability to perceive order consciously, and the ability to process information sequentially. The conscious perception of temporal order entails comparing the relative time of occurrence of each event and likely requires effort and attention. On the other hand, the ability to sequentially process successive events could happen subconsciously. Such subconscious processing might be useful for adaptive behaviour. For instance, Repp (2000a, 2000b) presented participants with an isochronous series of tones and asked them to tap on a key at the same time as the tones. By introducing small, but consistent, temporal perturbations in the series of tones (i.e. slightly longer or shorter intervals), a shift was induced between the taps produced by the participants and the tones. Even though this shift was less than the typical temporal order threshold (<20ms) and participants were unaware of the changes in the sequence, they nevertheless compensated for this shift and realigned their taps to the tones by taking into consideration the temporal order of the tap/tone event (whether the tap was before or after the tone). This compensatory behaviour therefore indicates discrimination of the relative order of two consecutive events (tap and tone) below the temporal order threshold.

More recently, in a multisensory paradigm, Van der Burg, Alais, & Cass (2018) asked participants to perform either temporal order judgments (TOJ trials) or simultaneity judgments (SJ trials) of audio-visual stimuli, in which either the visual or auditory stimulus was presented first. TOJ and SJ trials were presented alternately. When the modality of the first stimulus was e.g. visual in TOJ trials, the point of subjective simultaneity (PSS) in the SJ trials was shifted towards the visual modality. In other words, participants perceived stimuli as being synchronous when in fact the visual stimulus had preceded the auditory stimulus. Importantly, this was true whether performance on the TOJ trial had been correct or incorrect, indicating that even if participants had not accurately discriminated the temporal order of stimuli in the TOJ trials, order had nonetheless been processed implicitly and influenced performance of the subsequent SJ trial. Moreover, even when participants had to respond according to the spatial location (left/right) of audio-visual stimuli, the authors found the same shift in PSS for subsequent SJ trials. This provides evidence that temporal order had not only been processed implicitly but also *automatically* since participants were not focused on stimulus order but on their location.

Even the sequential order of two consecutive *unimodal* events can be processed implicitly. Lalanne et al. (2012) asked participants to judge whether two visual stimuli, presented on either side of a screen, were presented synchronously or asynchronously. Participants responded with the left hand if stimuli were synchronous and with the right hand if asynchronous. Crucially, this allowed a Simon effect to be measured, which is a response preference (faster or more accurate responses) for stimuli appearing on the same side of the screen as the hand used to make the response (Simon, 1969). Participants were more likely to judge stimuli as asynchronous (i.e. a right-hand response) when the stimulus appeared first on the left then on the right, but were more likely to judge them as synchronous (i.e. a left-hand response) when the stimulus appeared first on the right then on the left. This response bias for the position of the second stimulus suggests that, in addition to explicitly judging whether or not they were synchronous, participants had implicitly coded the sequential order of the two events. Strikingly, this bias was observed not only for stimuli separated by clearly perceptible asynchronies (e.g. 50ms) but also for those separated by asynchronies below the threshold for conscious perception (e.g. 17ms). Therefore, despite the fact that participants couldn't consciously perceive an asynchrony of 17ms, their behaviour was nevertheless subconsciously influenced by the relative order of the two events. Interestingly, the authors tested not only healthy controls on this paradigm, but also patients with schizophrenia. The same implicit, subconscious processing of asynchrony and sequential order were observed in schizophrenic patients except that the Simon effect now revealed a response bias for the stimulus that appeared *first* (Lalanne et al., 2012). This result adds to the literature indicating aberrant temporal sequencing in schizophrenia (Capa et al., 2014; Franck et al., 2005; Riemer, 2018).

Healthy participants' bias for processing the second of two stimuli, even those separated by only 17ms, was later replicated and extended using a temporal order judgement task (Poncelet & Giersch, 2015). In this study, trials began with two squares, which acted as priming stimuli, appearing either synchronously or asynchronously (17ms SOA) on the left or right of the screen. After a variable interval, the squares turned grey one after the other and participants judged their temporal order by pressing the button located on same side as the square that had turned grey first. Reaction times (RTs) were faster when the second of the two asynchronous primes was on the same side as the first square to turn grey. The second of the two primes therefore appeared to act as an exogenous spatial cue, shifting attention to that side of the screen and thereby enhancing processing of any stimuli that subsequently appeared there. Since the SOA separating the first and second prime was only 17ms (i.e. below the threshold for conscious perception of temporal order) this attentional bias once again suggests that participants' behaviour was subconsciously influenced by the relative temporal order of the two primes.

Such biases strongly suggest that at least some aspects of temporal order are processed even when stimuli are separated by an SOA below the temporal order threshold. However, demonstrating that participants' behaviour is influenced by the second of two stimuli is not quite the same as demonstrating that participants have processed the relative temporal order of the two stimuli. For example, it is possible that presentation of the first stimulus simply led to anticipation of the second, whose location then oriented attention. The results of Lalanne et al (2012) and Poncelet & Giersch (2015) did not provide any direct evidence that the two stimuli had been coded relative to one another. Therefore, to test the hypothesis that the sequential order of two events can be processed subconsciously, we designed a new paradigm in which participants could use the temporal order of two stimuli to guide performance on a subsequent task. In the Temporal Order-cued Reaction Time (TORT) task participants had to discriminate the shape of a target by pressing the appropriate response button as quickly as possible (e.g. index finger for +, middle finger for x). Targets were preceded by a cue, composed of two consecutive stimuli, one red and one green. Importantly, participants were told that the relative temporal order of these two colours predicted target shape. Therefore, if the participant successfully processed the order of the two stimuli, the appropriate motor response could be prepared in advance of target presentation. In the control condition, on the other hand, the two cue stimuli appeared simultaneously meaning that participants could not predict target shape and so could not prepare a particular motor response. If participants used the temporal order of the cue stimuli to predict target shape, responses should be faster in the order-cue condition than the control condition, thereby demonstrating processing of temporal order. Crucially, we measured performance when the SOA between the two cue stimuli was longer than the typical temporal order threshold of 20-40ms (66ms SOA) and when it was below this threshold (17ms SOA). To check whether these SOAs were respectively above and below the temporal order threshold, participants performed a separate temporal order judgment (TOJ) task using the same stimuli as those employed in the TORT task. We considered that any participant performing significantly better than chance in the 17ms SOA condition of the TOJ task might reflect the fact that they had consciously perceived temporal order, meaning their temporal order threshold would have been shorter than 17ms. These participants were therefore excluded from analysis. Reciprocally, we also excluded any participant performing at or near chance when stimuli were separated by a 66ms SOAs, suggesting that their temporal order threshold would have been longer than 66ms. In this way, we analysed TORT performance only in those participants whose TOJ performance was at or near chance in the 17ms SOA condition, and better than chance in the 66ms condition.

We hypothesized that when the SOA induced better-than-chance TOJ performance (66ms SOA), RTs would be faster in the order-cue condition than the control condition. If, on the other hand, the SOA had induced near-chance performance in the TOJ task (17ms SOA) but RTs were nevertheless faster for order-cue versus control conditions in the TORT task this would indicate that temporal order information had been processed in the TORT task and used to improve performance. If this were the case, it would provide evidence that temporal order can be processed subconsciously.

2.Experiment 1

2.1.Materials and methods

2.1.1.Subjects

Thirty-one healthy participants (mean age =26.5; SD = 5.3) volunteered for this experiment. They signed written, informed consent forms, accepting to participate in the study, which had been approved by a local ethics committee. They had normal or corrected-to-normal vision, were not colour-blind, and had no reported neurological or cognitive disorders. After analysing their performance in the temporal order judgment task (TOJ task), seven participants were excluded from the ANOVA analyses (6 participants responded better than chance in the 17ms SOA condition and 1 participant responded at chance in the 66ms SOA condition). The final sample therefore comprised twenty-four participants, including sixteen women and eight men (mean age = 26.2 years; SD = 4.6).

2.1.2.Experimental tasks

Stimuli were presented on a computer screen with 800x600 spatial resolution and 120Hz temporal resolution. The temporal precision of stimulus presentation (17ms or 66ms SOAs) was verified by a photodiode prior to the experiment. Participants sat at approximately 65-70 cm from the screen. Tasks were programmed with Eprime 3.0 Software, which controlled stimulus presentation and data collection.

Participants performed two tasks, each of which provided either a direct or indirect measure of temporal order processing (Reingold & Merikle, 1988; Schmidt & Vorberg, 2006). The temporal order-cued reaction time (TORT) task provided an indirect measure of temporal order processing by examining whether the temporal order of two consecutive cue stimuli could be used to guide subsequent RT performance. The temporal order judgment (TOJ) task provided a direct measure of temporal order processing and was used to verify, participant by participant, whether the temporal order of the cue stimuli used in the TORT task was above or below the threshold for conscious perception of temporal order.

2.1.2.1.Temporal order-cued RT (TORT) task

In the TORT task, temporal order processing was measured indirectly via choice reactions times to targets whose shape could be predicted by the temporal order of a prior cue. The task comprised three experimental conditions, each performed in a separate block in counterbalanced order. There were two order-cue conditions, in which the stimuli comprising the cue were separated by either a 17ms SOA or a 66ms SOA, and a control condition in which cue stimuli were presented simultaneously. Since Lin & Murray (2014) have shown that visual awareness of subliminal stimuli is increased when mixed with supraliminal stimuli ("priming of awareness"), the 17ms and 66ms SOAs were presented in separate blocks to minimise any artificial increase in perceptual awareness of temporal order in the 17ms SOA condition.

In all three conditions, a background image comprising two square frames, one above and one below central fixation, was present throughout the task. The centres of the square frames were 12cm apart, yielding a visual angle of about 10°. The central fixation point comprised a star surrounded by a circle. All trials began with presentation of the cue. In the two order-cue conditions, the cue consisted of two squares, coloured red or green, which were presented consecutively in a particular colour order (Figure 1Ai). The SOA between the onset of the first and second squares was 17ms in one block and 66ms in the other block. Therefore, first square was presented for 17ms (or 66ms) before then being accompanied by the second square. Both squares then remained on the screen for 242ms and disappeared simultaneously. In the control condition, the cue consisted of simultaneous presentation of two blue squares for 266ms (Figure 1B). After a variable interval of 608 or 1408ms, the target was presented on the screen until the participant made their response (or for a maximum of 2 seconds if no response). The target comprised one element of the central star that was highlighted to form one of three shapes: +, x, or o (Figure 1). Participants were instructed to respond to the target as quickly as possible, using the fingers of their right hand (index, middle or ring finger) according to the shape of the target (+, x, or o respectively). Crucially, in the order-cue conditions, participants were told that the temporal order in which the colours appeared could be used to predict the shape of the target. For example, if the red square appeared first followed by green (RG trials) then the target would be a +. Conversely, if green was presented first followed by red (GR trials) then the target would be an x. On the other hand, if the two consecutive squares were both the same colour, either both red (RR trials) or both green (GG trials), then the target would be an o. Participants could therefore use the temporal order information provided by the cue to prepare the appropriate motor response and thus speed their RTs. In the control condition, by contrast, participants were told that presentation of two blue squares would be simultaneous and would hold no predictive information. Nevertheless, they were instructed still to respond as quickly as possible to the shape of the target using the same finger associations as for the order-cue conditions (index, middle or ring finger for +, x or o targets respectively). The computer recorded both accuracy and speed of responses.

Importantly, stimulus colour was independent of stimulus location (e.g. the red square could appear first at either the top or bottom of the display). In spatially distributed displays, apparent motion has a strong influence on temporal order judgement performance (Cass & Van der Burg, 2014, 2019). However, by orthogonalising colour with respect to location, we ensured that the direction of apparent motion (upward or downward) had no consistent association with target shape. Instead, participants had to process the relative order of the two colours in order to successfully predict shape.

The association between temporal order of cue colours (RG, GR and RR/GG trials) and target shape (+, x, or o) was counterbalanced across participants. Half of all participants had the RR repetitive trials and the other half had the GG repetitive trials. The RR or GG trials were included to encourage participants to use *both* the first and second stimuli to predict target shape, rather than only one of these. Previous work by one of the co-authors has demonstrated that healthy participants preferentially process the second of two consecutively presented stimuli (Lalanne et al., 2012; Poncelet & Giersch, 2015). If we had included only RG and GR trials then a participant could theoretically predict target shape by focusing on the colour of the second square only: G would predict one shape and R would predict another. Since our aim was to examine whether participants could process the order in which two consecutive colours were presented, it was important that *both* stimuli be used to predict target shape. By including RR/GG trials in the block, target shape could no longer be uniquely predicted by processing only one of the two stimuli. For instance, if the second square were green this could indicate either an RG cue or a GG cue. Since these cues are associated with two different targets, it would be impossible to use the colour of the second square alone to predict target shape. In order to discriminate between the two possible cues, it would be necessary to also process the colour of the first square.

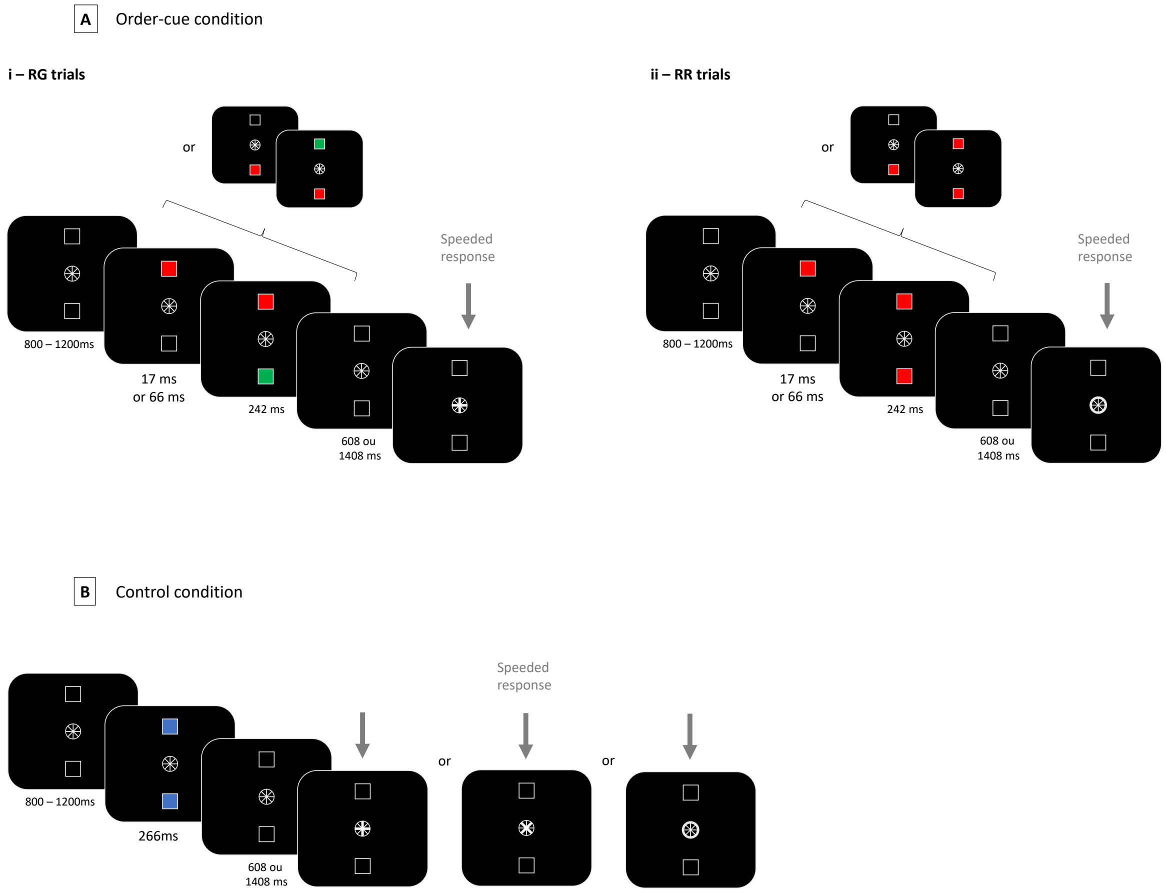

Figure 1 - Temporal order-cued RT (TORT) task. In all conditions, a coloured cue preceded a target to which participants made speeded choice responses. The cue and target were separated by a variable interval (608/1408ms) and trials were separated by a variable (800-1200ms) inter-trial interval. In order-cue conditions, the colours were presented consecutively and the SOA between colours was either 17ms or 66ms. In the control condition, the two blue squares were presented simultaneously. The target remained on the screen until the participant made their response (or for a maximum of 2 seconds if no response).

A - Order-cue condition: i - Two squares of different colours appeared consecutively in two locations in a particular temporal order: red then green (RG) or green then red (GR). Target location was orthogonal to target colour: for example, the red square could appear first either at the top or bottom of the screen. Each colour order was associated with one of three target shapes (+, x or o): in this example RG predicts that the target will be a +. ii - Alternatively, two squares of the same colour (either red (RR) for half of participants or green (GG) for the other half) could be presented in the two locations: in this example, RR predicts that the target will be a o. Participants made choice RTs to the shape of the central target and could use the temporal order of the preceding colours to predict its shape.

B - Control condition: Two blue squares were presented in two locations simultaneously. The simultaneous blue square was associated with all three target shapes. Participants made choice RTs to the shape of the central figure but could not predict its shape in advance.

Participants were familiarised with task instructions prior to testing. The familiarisation block for each experimental condition (17ms, 66ms, control) was given just prior to each corresponding test block. In the two order-cue conditions (17ms or 66ms), training consisted of 20 trials of the + target trials, 20 of the x target trials, 20 of the o target trials, and finally 12 trials comprising a random presentation of each of the three targets shapes. Participants performed 18 familiarisation trials, in which the three target shapes were presented randomly.

There were 108 test trials of the order-cue conditions (17ms or 66ms), comprising 36 trials each of the +, x and o target trials presented in randomised order and 72 trials of the control condition, comprising equal proportions of the three target shapes. The three experimental blocks were presented in random order, counterbalanced across participants. Cue-target association was partially counterbalanced with respect to block order (17ms/66ms/control). Although cue-target association was counterbalanced across participants (6 possible combinations of the association between RG, GR or RR/GG cues and +, x or o targets), as was the order of the three experimental blocks (6 possible combinations of the order of the 17ms, 66ms, and control conditions), we did not fully counterbalance block order with respect to cue-target association.

2.1.2.2.Temporal order judgment (TOJ) task

The TOJ task provided a direct measure of temporal order processing (Reingold & Merikle, 1988; Schmidt & Vorberg, 2006), allowing us to verify whether SOAs of 17 and 66ms were likely to be below or above, respectively, the temporal order threshold of our participants[1]. The TOJ task was always performed after the TORT task. We hypothesised that TOJ performance that was significantly better than chance would reflect conscious perception of temporal order, indicating that stimuli were separated by an SOA longer than the temporal order threshold. On the other hand, TOJ performance that was at chance, or near-chance, levels could indicate that temporal order had not been consciously perceived and so stimuli were separated by an SOA that was shorter than the temporal order threshold. Any participants performing above chance for stimuli with a 17ms SOA, or below chance for those with an 66ms SOAs, were excluded from ANOVA analyses. To prevent priming of awareness (Lin & Murray, 2014) the 17ms and 66ms SOA conditions were tested in separate blocks. For a given participant, the order of presentation of the 17ms or 66ms blocks was the same as that used in the TORT task. In order to match our direct and indirect measures of temporal order processing as closely as possible (Reingold & Merikle, 1988; Schmidt & Vorberg, 2006) the TOJ task used the same background image and cue stimuli as the TORT task (see Figure 1Ai). Therefore, two coloured squares appeared consecutively in a specific temporal order, either red then green (RG trials) or green then red (GR trials). The SOA between the two coloured squares was either 17ms or 66ms. By contrast with the TORT task, there was no subsequent target and instead participants had to judge the temporal order of the two colours by indicating which of the colours appeared first. Again, to match the two tasks as closely as possible, they used the same association between response finger and temporal order as in the TORT task. For example, if a participant had been trained to respond to RG trials using their index finger in the TORT task, then in the TOJ task they were asked to respond with their index finger if they perceived red first. For each block (17ms or 66ms) participants were first familiarized with task instructions by performing 8 training trials. They then performed 80 test trials, with 40 RG and 40 GR trials presented randomly. The computer recorded discrimination accuracy.

2.1.3.Data analysis

Statistical analyses were conducted with SPSS and R software and the threshold for significance was set at $p<0.05$ for all analyses. First, a χ^2 test was performed on individual participant's accuracy scores in the TOJ task in order to exclude any participants whose performance in the 17ms condition was

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[1] Temporal order thresholds typically vary between 20-40ms. Although we did not directly measure temporal order thresholds in the current study, we found that the average threshold for the same TOJ task was 46.6ms (SEM ± 3.92ms) in an independent group of 20 participants of similar age and gender ratio (mean age = 26 years; twelve women). In this independent experiment, the SOA between the red and green squares was either 17, 33, 50, 66 or 83ms (32 trials per SOA), and the temporal order threshold for each participant was defined as the SOA at which they would have correctly identified temporal order on 75% of trials.

significantly above chance (six participants out of a total of 31 tested) and participants whose performance in the 66ms condition was near chance or below (one participant out of a total of 31).

For the remaining sample of participants (n=24), we analysed mean RTs and accuracy (% correct) for the GR and RG trials of the TORT task. For both measures, we conducted 2x3 repeated-measures ANOVAs with cue (17ms SOA, 66ms SOA, simultaneous control) as a within-subjects factor and SOA order (17ms then 66ms, 66ms then 17ms) as a between-subjects factor. Trials with very slow (>1000ms) or very fast RTs (<100ms) were excluded (1.25% of total trials) from both analyses. In addition, RTs corresponding to incorrect responses (6.91% of total trials) were excluded from the analysis of RTs. These analyses allowed us to measure the benefit of order-cues on performance, whether order was consciously perceived (66ms SOA) or not (17ms SOA). Violations of sphericity were corrected using the Greenhouse-Geisser procedure.

In addition, to test whether participants used both squares to predict target shape or focused on only one of the squares, we performed a supplementary analysis of RG and GR trials in the 17ms and 66ms blocks. We reasoned that if participants used the colour of only e.g. the second square to predict target shape then participants in the RR group, for example, would process both GR and RR trials in the same way (in both case, the second square is red). However, since GR and RR trials predict different target shapes, this would create uncertainty about the target shape associated with cues in which the second square was red. By contrast, if the participant is processing only the second square, then RG trials predict with certainty the shape associated with cues in which the second square is green. RTs in the predictive RG trials would therefore be faster than those in the relatively non-predictive GR trials. If, however, participants processed the colour of both first *and* second squares, then RR, GR and RG trials would each uniquely predict a single target shape and RTs should be equally fast for GR and RG trials. To test these hypotheses, trials were divided according to whether the repetitive RR/GG trials shared a location with (1) the first square (i.e. RG trials for the RR participants and GR trials for the GG participants) (2) or the second square (i.e. GR trials for the RR participants and RG trials for the GG participants). In other words, we tested whether potential uncertainty regarding target shape would be more costly if it were associated with the first or second square. Data were analysed in a repeated measures ANOVA, with SOA (17ms SOA and 66ms SOA) and shared colour (first square, second square) as within-subject factors.

The 24 participants included in these ANOVAs were selected post-hoc, based on their performance in the TOJ task. Although it is common to use a direct measure of stimulus processing to select participants whose performance is tested on an indirect measure (see Shanks, 2017 for examples), it is more difficult to draw unambiguous conclusions when two different response metrics have been used for the direct (TOJ accuracy) and indirect (TORT RT) measures (Reingold & Merikle, 1988). Therefore, on the advice of an anonymous reviewer, we used RT data from the TORT task to model the level of TOJ accuracy that would have been needed to produce the RT benefit we observed in the 17ms SOA condition. If the observed TOJ accuracy score is significantly lower than the modelled TOJ score, this means that a TORT RT benefit has been found at a level of TOJ conscious perception lower than that predicted by the model. Data were modelled for each individual participant and we modelled data from the 7 excluded participants as well as the 24 included ones. Because the sample of 24 participants had been pre-selected based on their poor performance on the TOJ task, their TORT performance might have been higher than expected simply because of regression to the mean (Shanks, 2017). By including data from all 31 participants, we minimise the possibility that TORT performance had been artificially overestimated.

We modelled data as follows. For each individual participant, and for each condition (17ms, 66ms, control), we modelled their average RT as a weighted average of RTs corresponding to preparation of a correct response (RTcorrect) and those corresponding to preparation of an incorrect one (RTincorrect).

In the control condition, there is no cue and so we assume that they prepare the correct and incorrect response each 50% of the time:

Control RT = 0.5RTcorrect+0.5RTincorrect

In the 66ms SOA condition, we assume each participant prepare the correct and incorrect response at the same rate as in the TOJ task:

66msSOA RT = (%TOJcorrect)RTcorrect + (%TOJincorrect)RTincorrect

Using the observed average RT for the control and 66ms SOA conditions for each individual participant, we can calculate RTcorrect and RTincorrect. These values were then used, along with the participant's average RT in the 17ms condition, to calculate the %TOJcorrect that would be predicted to result in that 17ms condition RT. The difference between modelled and observed %TOJcorrect was assessed with a paired t-test.

2.2.Results

2.2.1.TOJ task:

A χ^2 test of the percentage of correct order judgements revealed that among our thirty-one participants, six participants correctly judged the temporal order of two stimuli separated by a 17ms SOA at a rate greater than chance (mean = 64.38 % correct, range 61.25 - 68.75 %). This indicates that these participants had some conscious perception of the temporal order of two stimuli, even when separated by an SOA of only 17ms. Since the aim of the study was to examine whether temporal order information presented *below* the threshold for conscious perception of order could nevertheless be processed to guide performance, the six participants for whom a 17ms SOA produced better-than-chance performance in the TOJ task were excluded from the ANOVA analyses. In addition, we also excluded one other participant whose temporal order judgements were no better than chance (50.65 % correct) when stimuli were separated by a clearly perceptible 66ms SOA (Figure 2A).

The remaining 24 participants judged the temporal order of two stimuli separated by a 17ms SOA near chance level (mean = 52.19 %; SD = 4.61) and the order of stimuli separated by a 66ms SOA at a rate considerably greater than chance (mean = 85.90 %; SD = 11.46) (Figure 2B). This indicates that the 24 participants included in the statistical analyses did not consciously perceive the order of the cue stimuli when they were separated by a 17ms SOA but did perceive it consciously if separated by a 66ms SOA.

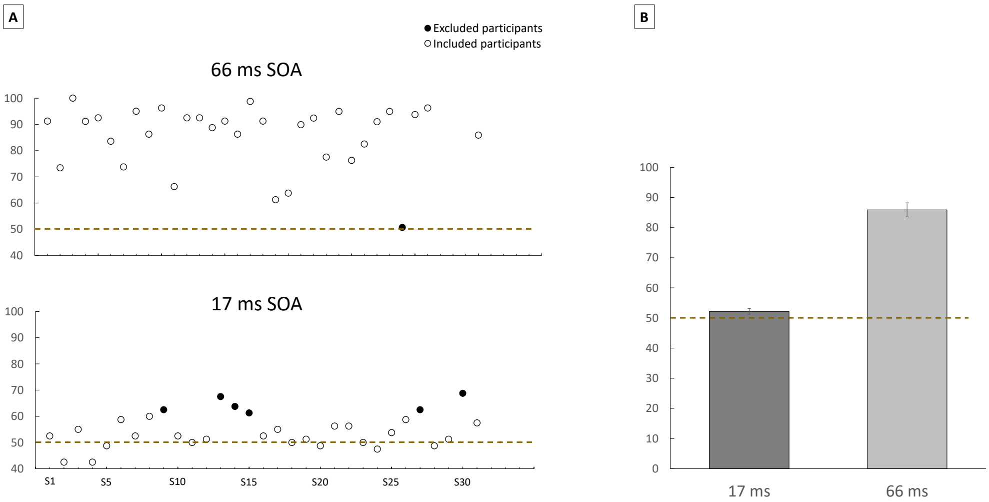

Figure 2 – A – Percentage of correct order judgments for each of the 31 participants in the TOJ task for the 66ms SOA condition and the 17ms SOA condition. Black dots corresponded to the 7 participants excluded from the ANOVA analyses. B – Mean percentage of correct order judgments for the remaining 24 participants for the 66ms SOA condition and the 17ms SOA condition. Error bars represent the standard error (SEM).

2.2.2.TORT task:

To examine whether temporal order could be used to guide performance, we compared RTs in RG and GR order-cue trials to RTs in control trials. The ANOVA indicated a significant main effect of cue ($F_{2,44} = 72.089$; $p < 0.0001$; partial eta = 0.766). Planned pairwise comparisons indicated that participants had faster RTs for the order-cue conditions than the control condition (Figure 3), whether the cue stimuli were separated by a 17ms SOA ($p<0.0001$) or a 66ms SOA ($p<0.0001$). In addition, RTs were faster for the 66ms SOA condition than the 17ms SOA condition ($p<0.0001$). There was a significant interaction between cue and the order in which the 17ms or 66ms blocks were performed ($F_{2,44}= 6.721$; $p = 0.01$; partial eta = 0.234), with the RT benefit for the 66ms condition being greater when the 66ms block was performed second ($p < 0.0001$) rather than first ($p = 0.001$) whereas the RT benefit for the 17ms condition was greater when it was performed first ($p < 0.0001$) rather than second ($p = 0.004$). There was no main effect of block order ($F_{1,22} = 0.039$; $p = 0.846$; partial eta = 0.002).

One potential caveat to our findings is that the TORT task provides confirmation of the order-shape association on every single trial: the order-cue is always followed by the target shape to which it is associated (100% validity). Presentation of a particular shape in the TORT task could therefore confirm (post-hoc) the order a participant thinks they might have seen. This trial-by-trial confirmation is not present in the TOJ task. Although such post-hoc confirmation could not retrospectively modulate the pre-target motor preparation processes necessary to speed RTs on a trial-by-trial basis, it might disproportionately enhance temporal order processing in the TORT task over time. If so, we would expect RTs to get progressively faster throughout the block as the participant overlearns the association between order and shape. However, RTs did not show this pattern in either the 66ms condition or, importantly, the 17ms one. To test this, RTs were grouped into four chronologically ordered time-bins (i.e. trials 1-18; 19-36; 37-54; and 55-72) and a 2x4 repeated-measure ANOVA was conducted with time-bin and cue (17 or 66ms) as within-subjects factors. Although there was a significant effect of time-bin ($F_{3.69} = 4.897$, $p = 0.004$, partial eta = 0.176) RTs actually got *slower* over time for both the 66ms condition (mean RT in time-bin 1-4 was 382ms; 399ms; 417ms; 407ms respectively) and 17ms condition (mean RT 464ms; 477ms; 490ms; 493ms). A significant main effect of cue ($F_{1.23} = 56.345$, $p < 0.001$, partial eta = 0.71) simply confirmed that RTs were faster for the 66ms condition than the 17ms condition, and there was no interaction between cue and time-bin ($F_{3.69} = 0.267$, $p = 0.849$, partial eta = 0.011). Therefore, RT did not get faster over time, suggesting participants were not using trial-by-trial confirmation of the cue-target association in the 17ms and 66ms conditions to improve temporal order processing in the TORT task.

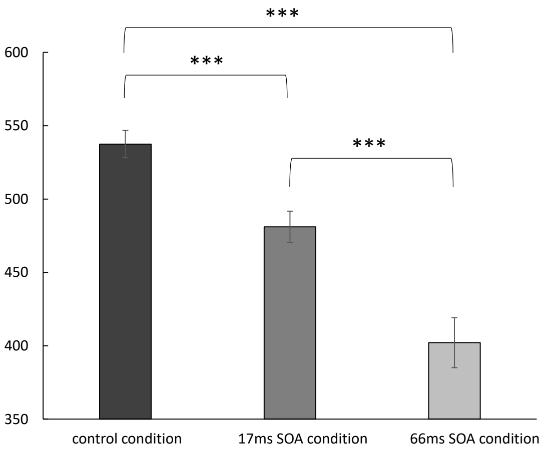

*Figure 3 - Mean RTs (N=24) for the 17ms SOA, 66ms SOA and control conditions of the TORT task. Participants RTs were significantly faster when target shape could be predicted by the temporal order of the squares' colour than when its shape could not be predicted in the control condition. Importantly, this effect was significant whether squares were separated by a subliminal (17ms) or supraliminal (66ms) SOA. Error bars represent SEM. *** = p < 0.0001*

The analysis of accuracy (percentage correct) also revealed a significant main effect of cue ($F_{2,44}$ = 5.911; p = 0.013; partial eta = 0.212). Planned pairwise comparisons indicated that participants were more accurate in the control condition (94.94%) than the order-cue conditions (91.9% for the 17ms SOA; 92.2% for the 66ms SOA), whether the cue stimuli were separated by a 17ms SOA (p = 0.014) or a 66ms SOA (p = 0.001). There was no significant difference between the 66ms and 17ms SOA conditions (p > 0.5). There was no significant effect of the order in which the 17ms or 66ms blocks were performed ($F_{1,22}$ = 0.517; p = 0.480; partial eta = 0.023) nor interaction between cue and block order ($F_{2,44}$= 0.959; p = 0.366; partial eta = 0.042). Since accuracy was lower in the order-cue conditions, and RTs were faster (see above), this suggests the presence of a speed-accuracy trade-off. To investigate this further we conducted a correlation between the RT benefit of temporal order cues and the cost in accuracy induced by these order cues. The RT benefit per participant was calculated as [(meanRT17ms – meanRTcontrol)/meanRTcontrol] or [meanRT66ms-meanRTcontrol/meanRTcontrol] and the accuracy cost was calculated as [(mean%correct17ms - mean%correct_control)/mean%correct_control] or [(mean%correct66ms - mean%correct_control)/mean%correct_control]. Across participants, there was a significant correlation between the RT benefit and the accuracy cost of temporal order cues, for the 17ms SOA condition (Spearman R = 0.441; p = 0.031) though not for the 66ms SOA condition (Spearman R = - 0.237; p = 0.265).

An additional ANOVA was conducted to examine whether participants used the relative temporal order of *both* stimuli to guide performance, or whether they used only the first or second of the two consecutive stimuli. There was no significant main effect of shared colour ($F_{1,23}$ = 0.026; p = 0.873; partial eta = 0.001), indicating that participants used both stimuli to make their prediction rather than processing only the first or second. Mean RTs revealed that RTs were identical whether it was the first (mean RT = 480.36ms for the 17ms SOA; mean RT = 403.75ms for the 66ms SOA) or the second (mean RT = 482.18ms for the 17ms SOA; mean RT = 400.38ms for 66ms SOA) square that shared a colour with the repetitive RR/GG trials. There was a significant mean effect of SOA ($F_{1,23}$ = 53.348; p < 0.0001; partial eta = 0.699), which simply replicated results of the previous ANOVA demonstrating that RTs were faster when stimuli were separated by 66ms (mean RT=402.1ms) than by 17ms (mean RT= 481.04ms).

There was no significant interaction between SOA and shared colour ($F_{1,23} = 0.254$; $p = 0.619$; partial eta = 0.011), indicating that participants used both of the two squares to predict target shape whether the temporal order of the two squares was consciously perceptible or not.

2.2.3.Modelling TOJ performance from TORT RTs:

For each of the original 31 participants, we calculated the TOJ accuracy score in the 17ms SOA condition that would have been necessary to produce the RT observed in the 17ms condition of the TORT task. The model predicted that, on average, participants would have had to report order correctly on 66.2±2.3% of trials in the TOJ task to obtain the RT that we observed in the TORT task. However, participants, on average, reported order correctly on only 54.5±1.2% of trials. In other words, the RT effect we found in the TORT task was observed at a level of TOJ accuracy lower than that predicted by the model. This effect was significant whether we tested the entire group of 31 participants ($t(30) = 5.66$; $p < 0.0001$) or only the sample of 24 participants included in the ANOVAs ($t(23) = 5.15$; $p < 0.0001$).

2.3.Discussion

We used a novel paradigm (TORT task) to test whether the temporal order of two consecutive stimuli could be used to predict the shape of a subsequent target, even when their order could not be consciously perceived. The order of two coloured squares (red then green (RG), or vice versa (GR)) predicted target shape, and RTs to detect the target were used as an indirect measure of temporal order processing. Participants' ability to consciously perceive temporal order at SOAs of 17ms or 66ms was measured directly in a separate TOJ task. We found that response times (RTs) in the TORT task were faster in the 66ms SOA order-cue condition compared to a non-predictive control condition, indicating that participants were able to use consciously perceived order to predict target shape and so speed RTs. Crucially, RT benefits were still present for the 17ms SOA order-cue condition compared to the control condition. Since participants were performing near chance when stimuli were separated by a 17ms SOA in the TOJ task, it is unlikely that this RT benefit was due to conscious perception of temporal order. Instead, our results indicate that participants were able to use the cue to optimise performance even though the temporal order of the two squares was not perceived consciously. However, the RT benefit of the 17ms SOA cue was associated with a corresponding decrease in accuracy, suggesting these results may be partially explained by a speed-accuracy trade-off. Indeed, speed-accuracy trade-offs have already been reported for subconscious, as well as conscious, stimuli (Reuss et al., 2015). Of course, RTs were measured in correct trials only and so the faster RTs in the order-cue conditions cannot simply reflect the influence of fast, impulsive errors. In addition, participants responded correctly in the great majority of trials (>90%) meaning that they weren't simply guessing. However, it's still possible that participants may have adopted a general response strategy that prioritised speed over accuracy to a greater extent in the 17ms condition than the control condition.

The TORT paradigm included trials in which the two consecutive stimuli were of the same colour (RR/GG trials). These trials were included to encourage processing of both stimuli, rather than only one or the other. This is important because prior simultaneity judgement experiments have shown that participants preferentially process the second of two consecutively presented stimuli (Lalanne et al., 2012; Poncelet & Giersch, 2015). However, in the current study we found that participants used both stimuli to guide performance, showing no clear preference for processing one or the other. One of the main experimental differences was that temporal order was defined by stimulus colour in our own experiment (e.g. red then green), but by stimulus location (e.g. left then right) in previous experiments. The discrepancy in results suggests that the reported processing bias for the second stimulus might be present only when temporal order is defined in spatial terms. This hypothesis could be directly tested in future experiments. More importantly however, the lack of processing bias for the first or second stimulus in our own paradigm means that the experiment can now be repeated without the inclusion of the RR/GG trials. This is important because their inclusion actually resulted in an unforeseen confound that could potentially explain our pattern of results. The order-cue conditions and the control condition were matched in terms of the number of response choices: both conditions comprised three response choices for three possible targets. However, in the order-cue conditions, two different colours were presented in the RG/GR trials but only one colour was presented in the RR/GG trials. This means that if participants simply perceived that two different colours had been presented, whatever their temporal order, they could eliminate the possibility that the target corresponding to the RR/GG cue would be presented. Therefore, the number of possible targets, and so the number of possible response choices, in the order-cue condition would actually be two rather than three. By contrast, in the control condition, the cue is entirely non-predictive and so the number of possible targets, and therefore response choices, is still three. The Hick-Hyman law states that the more response choices there are, the longer the response time will be (Hick, 1952; Hyman, 1953). Since the number of response choices could be argued to be smaller in the order-cue condition than the control condition, the faster responses observed in the order-cue conditions could simply be explained by fewer response choices. To verify that our results were due to temporal order processing and not just due to a difference in the number of response choices, we conducted a second experiment similar in every respect to Experiment 1 except that we removed the GG (or RR) trials in the order-cue condition and the third target colour in the control condition. This left just two possible response choices in each condition. If we still observe faster responses in the order-cue condition compared to the control condition at an SOA of 17ms, we can conclude that this effect is not due to differences in the number of response choices but to subconscious temporal order processing.

3.Experiment 2

3.1.Materials and methods

3.1.1.Subjects

Twenty-eight healthy participants (mean age =22.9; SD = 4), two of them having also performed the first experiment, volunteered for this experiment. They signed written, informed consent forms, accepting to participate in the study, which had been approved by a local ethics committee. They had normal or corrected-to-normal vision, were not colour-blind, and had no reported neurological or cognitive disorders. After analysing their performance in the temporal order judgment task (TOJ task), four participants were excluded from all further analyses (3 participants responded better than chance in the 17ms SOA condition and 1 participant responded near chance in the 66ms SOA condition). The final sample therefore comprised twenty-four participants, including seventeen women and seven men (mean age = 22.9 years; SD = 3.9).

3.1.2.Experimental tasks

In this second experiment, stimuli in the TORT and TOJ task were identical to those used in Experiment 1 (Figure 1), except that trials including the target 'o' were removed.

3.1.2.1.Temporal order-cued RT (TORT) task

We used the same three experimental conditions as in Experiment 1, each presented in a separate block in counterbalanced order: two order-cue conditions (17ms or 66ms SOA), and a control condition (simultaneous). In all conditions, stimulus presentation was identical to Experiment 1 except for the removal of all trials ending with the target "o", resulting in a two-choice cued RT task (equivalent to Figure 1Ai) rather than a three-choice task. As such, the RR/GG trials were removed from the order-cue conditions. In all conditions, the cue (RG, GR or control) was followed by one of two targets: + or x. Participants were asked to respond as quickly as possible to the target by responding to the + with their index finger and to the x with their middle finger. Participants were informed of the association between cue order and target shape, which was counterbalanced across participants.

The familiarisation block for each experimental condition was given just prior to each corresponding test block. In the order-cue conditions (17ms or 66ms), training consisted of 20 trials of the + target trials and 20 of the x target trials and finally 12 trials comprising a random presentation of each of the two target shapes. For the control condition, participants performed 18 familiarisation trials, in which the two target shapes were presented randomly. There were 72 test trials of each of the order-cue conditions (17ms or 66ms) and 72 trials of the control condition. In each condition there were equal proportions of the two target shapes trials (36 trials of each) presented in randomised order. The three experimental blocks were presented in random order, counterbalanced across participants.

3.1.2.2.Temporal order judgment (TOJ) task

The TOJ task was exactly the same as in Experiment 1. Participants had to judge the temporal order of two consecutive coloured squares by indicating which of the colours appeared first.

3.1.3.Data analysis

Statistical analyses were conducted with SPSS and R software and the threshold for significance was set at $p < 0.05$ for all analyses. We repeated the same analyses as in Experiment 1. First, a χ^2 test was performed on individual participant's accuracy scores in the TOJ task. Of the 28 participants, four had to be excluded, comprising three whose performance was significantly above chance for the 17ms condition and one whose performance was near chance for the 66ms condition.

For the remaining sample of participants (n=24), we conducted 2x3 repeated-measures ANOVAs of mean RTs and accuracy (%correct) in the GR and RG trials of the TORT task, with cue (17ms SOA, 66ms SOA, simultaneous control) as a within-subjects factor and SOA order (17ms then 66ms, 66ms then 17ms) as a between-subjects factor. Very slow (>1000ms) or very fast RTs (<100ms) were first excluded (0.81% of total trials) from both analyses and RTs corresponding to incorrect responses (6.83% of total trials) were excluded from the RT analysis. Finally, as in Experiment 1, we modelled the level of TOJ accuracy that would have been needed to produce the RT benefit observed in the 17ms SOA condition for all 28 participants. The difference between modelled and observed %TOJcorrect was assessed with a paired t-test.

3.2.Results

3.2.1.TOJ task:

A χ^2 test of the percentage of correct temporal order judgements revealed that among our twenty-eight participants, three participants correctly judged the temporal order of two stimuli separated by a 17ms SOA at a rate greater than chance (mean = 65 % correct, range 62.5 – 67.5 %) and one other participant had temporal order judgements that were no better than chance (57.5 % correct) when stimuli were separated by a clearly perceptible 66ms SOA. These four participants were therefore excluded from the ANOVA analyses.

The remaining 24 participants judged the temporal order of two stimuli separated by a 17ms SOA near chance level (mean = 51.2 %; SD = 4.8) and the order of stimuli separated by a 66ms SOA at a rate considerably greater than chance (mean 85.3 %; SD = 9.69). This indicates that the 24 participants included in the ANOVA analyses did not consciously perceive the order of the cue stimuli when they were separated by a 17ms SOA but did perceive it consciously if separated by a 66ms SOA.

3.2.2.TORT task:

The ANOVA comparing RTs in the RG and GR order-cue trials to RTs in the control trials indicated a significant effect of cue ($F_{2,44} = 41.780$; $p < 0.0001$; partial eta = 0.655). Planned pairwise comparisons indicated that participants had faster RTs for the order-cue conditions than the control condition (Figure 4). Importantly, this effect was significant whether the cue stimuli were separated by a 17ms SOA ($p<0.03$) or a 66ms SOA ($p<0.0001$). In addition, RTs were faster for the 66ms SOA condition than the 17ms SOA condition ($p<0.0001$). There was no significant interaction between cue and the order in which the 17ms or 66ms blocks were performed ($F_{2,44} = 1.635$; $p = 0.207$; partial eta = 0.069) and no main effect of block order ($F_{1,22} = 0.595$; $p = 0.449$; partial eta = 0.026).

As in the first experiment, we examined whether RTs got faster over time in the TORT task. A 2x4 repeated-measure ANOVA was conducted with time-bin and cue (17 or 66ms) as within-subject factors. A significant effect of time ($F_{3.69} = 8.887$, $p < 0.001$, partial eta = 0.279) again revealed that RTs got slower over time in both the 66ms condition (mean RT in time-bin 1-4 was 352ms, 395ms, 400ms, and 408ms respectively) and the 17ms condition (mean RT 449ms, 457ms, 474ms, 474ms). An effect of cue was observed ($F_{1,23} = 43{,}491$, $p < 0.001$, partial eta = 0.654), simply confirming that RTs in the 66ms condition were faster than those in the 17ms condition, and there was no interaction between cue and time-bin ($F_{3.69} = 2.329$, $p = 0.082$, partial eta = 0.092). Again, these results indicate that repeated presentation of the cue-target association in the TORT task did not improve temporal order processing over time.

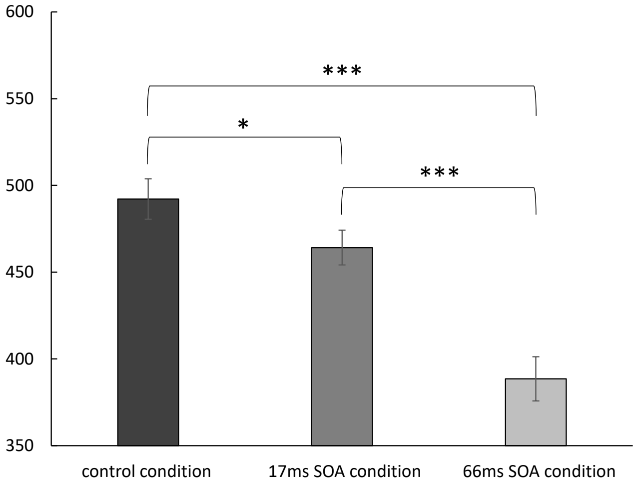

*Figure 4 - Mean RTs (N=24) for the 17ms SOA, 66ms SOA and control conditions of the TORT task, when only two response choices were possible. Participants RTs were significantly faster when target shape could be predicted by the temporal order of stimulus colour than when its shape could not be predicted in the control condition. These effects were significant whether stimuli were separated by a subliminal (17ms) or supraliminal (66ms) interval. Error bars are SEM. *** = $p < 0.0001$; * = $0.01 < p < 0.05$*

The ANOVA of accuracy scores also revealed a significant main effect of cue ($F_{2,44} = 12.568$; $p < 0.001$; partial eta = 0.364). Planned pairwise comparisons indicated that participants were more accurate in the control condition (95.74%) than the order-cue conditions (91.16% for the 17ms SOA; 92.29% for the 66ms SOA), whether the cue stimuli were separated by a 17ms SOA ($p<0.001$) or a 66ms SOA ($p = 0.001$). There was no significant difference between the 66ms and 17ms SOA conditions ($p>0.5$). There was no significant effect of the order in which the 17ms or 66ms blocks were performed ($F_{1,22} = 0.240$; $p = 0.629$; partial eta = 0.011) nor interaction between cue and block order ($F_{2,44} = 0.447$; $p = 0.642$; partial eta = 0.020). As in Experiment 1, we conducted a correlation between the RT benefit and the accuracy cost of temporal order cues. Across participants, there was no significant correlation between the RT benefit and the accuracy cost, either for the 17ms SOA condition (Spearman R = 0.127; $p = 0.554$) or the 66ms SOA condition (Spearman R = 0.030; $p = 0.888$). In other words, the participants whose RTs were speeded by the provision of temporal order cues were not the same as those whose accuracy was impaired.

3.2.3.Modelling TOJ performance from TORT RTs:

Our model predicted that, on average, participants would have had to report order correctly on 61.4±3.2% of trials in the 17ms condition of the TOJ task to obtain the RT we observed in the 17ms condition of the TORT task. However, participants, on average, reported order correctly on only 52.8±1.2% of trials. Crucially, the observed TOJ performance was significantly lower than predicted performance, whether we tested the entire group of 28 participants ($t(27) = 2.25$; $p = 0.033$ or only the 24 participants included in the ANOVAs ($t(23) = 2.56$; $p = 0.0175$).

3.3. Discussion

We found the same RT pattern as in the first experiment, with responses to the target being faster in the 66ms and 17ms SOA order-cue conditions than the control condition. By more carefully matching the number of response choices between the control condition and the order-cue conditions in this experiment (by eliminating the ‘o’ target trials in all conditions), we therefore confirmed that the faster responses in the 17ms SOA order-cue condition compared to the control condition in Experiment 1 was not just due to a difference in response choices across conditions. However, it is interesting to note that the difference in RTs for the 17ms SOA condition compared to the control condition is smaller in this experiment than in the first experiment (RT gain of 56.4 ms for Experiment 1; 28 ms for Experiment 2). This indicates that a part of the RT gain observed in the first experiment may indeed have been due to differences in the number of response choices between conditions. Nevertheless, the fact that RTs were still significantly faster in the 17ms SOA condition compared to the control condition in Experiment 2 confirms that temporal order was processed subconsciously and helped guide behaviour.

As in Experiment 1, participants made significantly more errors in the order-cue conditions of the TORT task than in the control condition. Although errors were relatively rare (5-8%), this pattern of results might reflect the influence of a speed-accuracy trade-off. However, and in contrast to the results of Experiment 1, the participants whose RTs benefitted most from the order cues were not the same as those who made the greatest number of errors. This suggests a dissociation in the effects of the cues on speed and accuracy. Moreover, and in contrast to the pattern of effect on RTs, the error rate was the same whether temporal order was consciously perceptible or not. This suggests that higher error rates in the order-cue conditions are induced by an experimental factor that is independent of the level of conscious perception.

4.General Discussion

We used a novel cued RT paradigm (TORT task) to test whether the temporal order of two consecutive stimuli could be used to guide performance, even though their relative order could not be consciously perceived. Choice RTs to a target were faster when participants could use the temporal order of a cue stimulus to predict target identity in advance, as compared to a non-predictive control condition. Critically, this result was observed whether the temporal order of the cue stimuli was consciously perceptible (66ms SOA) or not (17ms).

In a separate temporal order judgement (TOJ) task, participants performed near chance when stimuli were separated by a 17ms SOA, suggesting that they could not consciously perceive temporal order at such short SOAs. Chance TOJ performance was not simply due to poor understanding of task instructions since accuracy was high when stimuli were separated by a clearly perceptible 66ms SOA. Yet despite poor performance in the TOJ task for 17ms SOA stimuli, participants were nevertheless able to use exactly the same stimuli in the TORT task to predict target shape and so improve response speed. Moreover, when we modelled the level of TOJ performance that would theoretically have been needed to produce the RT benefit found in the 17ms SOA condition, it was significantly higher than that actually observed. In other words, the RT benefits in the TORT task were found at a level of TOJ conscious perception that was significantly worse (i.e. closer to chance) than that predicted by the model. These results suggest that the temporal order of two consecutive stimuli can be perceived subconsciously and used to guide behaviour.

Stimulus characteristics can play an important role in the ability to perceive temporal order more or less easily. For example, it is easier to process temporal order when it's defined by spatial characteristics (e.g. size, position) than by colour (Fink et al., 2006; McFarland et al., 1998). Depending on the distance and time interval between two consecutive stimuli, a percept of apparent motion can be induced (Gepshtein & Kubovy, 2007; Strybel et al., 1990), which helps improve the accuracy of temporal order judgements (Cass & Van der Burg, 2014, 2019; Spence et al., 2003). However, by orthogonalising colour with respect to location in our paradigm, there was no consistent association between the direction of apparent motion (upward/downward) and the order of the colours. Therefore, even if participants had been processing motion incidentally it would not help them to correctly identify the colour order and so they could not successfully predict target shape.

There is a clear distinction between neural processing of information on the one hand and being conscious of this processing, or of the stimuli conveying that information, on the other. Many cognitive processes are performed without being consciously aware of them (Kouider & Dehaene, 2007; Velmans, 1991). For example, the hemianopic patient DB could correctly discriminate stimuli presented in his blind field even though he did not consciously perceive them (Weiskrantz et al., 1974). The phenomenon of blindsight (Ajina & Bridge, 2017; Boyer et al., 2005; Weiskrantz et al., 1974), or the effects of masked priming (Dehaene et al., 1998; Del Cul et al., 2007; Kouider & Dehaene, 2007; Pesciarelli et al., 2019), illustrate how visual stimuli can be processed even though they have not been consciously perceived. Herzog, Kammer, & Scharnowski (2016) have proposed a two-stage model in which visual information is first processed subconsciously before then being integrated into a conscious perception. More interestingly, they suggest that subconscious processing has a higher temporal resolution than conscious perception (see also Giersch, Lalanne, Van Assche, & Elliott, 2013; Lalanne et al., 2012; Poncelet & Giersch, 2015). Our own results support this two-stage model, with stimuli separated by a 17ms SOA being subconsciously processed in the TORT task but not consciously perceived in the TOJ task. Moreover, stimulus order was processed sufficiently well to be able to improve subsequent motor responding to targets in the TORT task. Nevertheless, we found that the RT benefit was significantly greater in the 66ms SOA condition than the 17ms SOA condition. This means participants were better able to use the temporal order of two consecutive stimuli to predict target identity when it was consciously perceived. Therefore, even though action can be modulated by subconscious processing, conscious control nevertheless further modulates performance. In our case, we hypothesise that subconscious temporal order processing drives initiation of the motor response, whether stimuli were consciously perceptible or not. Conscious perception of temporal order might then influence subsequent stages of motor programming so as to improve performance even more.

Our results indicate that temporal order can be processed subconsciously. However, this does not necessarily imply that temporal order is processed automatically. Posner & Snyder (1975) defined an automatic process as occurring "without intention, without any conscious awareness, and without interference with other mental activity". The major distinction between subconscious processing and automatic processing is that in the former stimuli are not consciously perceptible despite task instructions to try and perceive them, while in the latter stimuli might be perceived consciously but no instructions have been given to process them. In the TORT task, participants were aware of the association between the temporal order of the cue and the shape of the target and so our results cannot address the automaticity of temporal order processing. Although some investigators suggest that automatic temporal order processing does not exist (Naveh-Benjamin, 1990), others have reported results in its favour (Van der Burg et al., 2018). It would be informative to repeat the TORT paradigm without informing participants of the predictive information conveyed by the cue in order to test whether the RT gain was due only to a top-down effect related to task instructions or to a more automatic bottom-up effect.

We imposed the constraint that participants had to be able to consciously perceive the temporal order of the two cue stimuli in the 66ms condition of the TOJ task, but *not* to consciously perceive their order in the 17ms condition. Nevertheless, 11 participants out of 59 (seven participants from the original sample of 31 volunteers for Experiments 1 and four participants from the original sample of 28 volunteers in Experiment 2) (i.e. 20%) had to be excluded because of above-chance performance in the 17ms SOA condition, or below-chance performance in the 66ms SOA condition. This implies a considerable degree of variability in temporal order thresholds between participants. There is a burgeoning literature indicating that individual differences in temporal order thresholds could be explained by individual differences in the frequency of neural oscillations, specifically the alpha rhythm. For example, there is a significant correlation between occipital alpha rhythm and the fusion threshold of two consecutive events: the higher the alpha frequency the better the participants' temporal resolution (Samaha & Postle, 2015). In the future, it would be informative to measure alpha rhythms during performance of the TOJ task to determine whether alpha frequency could predict whether or not the temporal order of two stimuli separated by e.g. 17ms is consciously perceptible or not.

5.Acknowledgments

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