



HAL
open science

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

Morgane Chassignolle, Anne Giersch, Jennifer T Coull

► To cite this version:

Morgane Chassignolle, Anne Giersch, Jennifer T Coull. Evidence for visual temporal order processing below the threshold for conscious perception. *Cognition*, 2021, 207, pp.104528. 10.1016/j.cognition.2020.104528 . hal-03193826

HAL Id: hal-03193826

<https://amu.hal.science/hal-03193826>

Submitted on 29 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

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

Authors: Chassignolle M^{1*}, Giersch A², Coull JT¹

¹ Laboratoire de Neurosciences Cognitives UMR 7291, Aix-Marseille University, CNRS, Marseille, France ² Unité de recherche 1114, INSERM, Strasbourg University, Strasbourg, France

*Corresponding author

Laboratoire de Neurosciences Cognitives
Aix-Marseille University, CNRS
3 place Victor Hugo,
13331 Marseille cedex 3,
France

morgane.chassignolle@gmail.com

+ 33 413550936

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 1.Introduction

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

8 A classic paradigm for studying the processing of temporal order is the temporal order judgment (TOJ)
9 task, which consists of presenting two consecutive stimuli separated by a very brief delay (the “stimulus
10 onset asynchrony” (SOA)) and asking participants which of the two stimuli appeared first. Many studies
11 demonstrate that the temporal order of two stimuli can be perceived at an inter-stimulus interval of at
12 least 20-40ms (Hirsh, 1959; Hirsh & Sherrick Jr, 1961; Kanabus et al., 2002; Pastore & Farrington,
13 1996; Pöppel, 1997), known as the temporal order threshold. Intriguingly, even though the auditory
14 system has better temporal resolution than the visual one (Wittmann, 1999, 2011), the temporal order
15 threshold is similar across visual, auditory and tactile modalities (Hirsh & Sherrick Jr, 1961; Kanabus
16 et al., 2002; Wittmann, 1999, 2011).

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

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

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

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

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

90 Such biases strongly suggest that at least some aspects of temporal order are processed even when
91 stimuli are separated by an SOA below the temporal order threshold. However, demonstrating that
92 participants' behaviour is influenced by the second of two stimuli is not quite the same as demonstrating
93 that participants have processed the relative temporal order of the two stimuli. For example, it is possible
94 that presentation of the first stimulus simply led to anticipation of the second, whose location then
95 oriented attention. The results of Lalanne et al (2012) and Poncelet & Giersch (2015) did not provide
96 any direct evidence that the two stimuli had been coded relative to one another. Therefore, to test the
97 hypothesis that the sequential order of two events can be processed subconsciously, we designed a new
98 paradigm in which participants could use the temporal order of two stimuli to guide performance on a
99 subsequent task. In the Temporal Order-cued Reaction Time (TORT) task participants had to
100 discriminate the shape of a target by pressing the appropriate response button as quickly as possible (e.g.
101 index finger for +, middle finger for x). Targets were preceded by a cue, composed of two consecutive
102 stimuli, one red and one green. Importantly, participants were told that the relative temporal order of
103 these two colours predicted target shape. Therefore, if the participant successfully processed the order
104 of the two stimuli, the appropriate motor response could be prepared in advance of target presentation.
105 In the control condition, on the other hand, the two cue stimuli appeared simultaneously meaning that
106 participants could not predict target shape and so could not prepare a particular motor response. If
107 participants used the temporal order of the cue stimuli to predict target shape, responses should be faster
108 in the order-cue condition than the control condition, thereby demonstrating processing of temporal
109 order. Crucially, we measured performance when the SOA between the two cue stimuli was longer than
110 the typical temporal order threshold of 20-40ms (66ms SOA) and when it was below this threshold
111 (17ms SOA). To check whether these SOAs were respectively above and below the temporal order
112 threshold, participants performed a separate temporal order judgment (TOJ) task using the same stimuli
113 as those employed in the TORT task. We considered that any participant performing significantly better
114 than chance in the 17ms SOA condition of the TOJ task might reflect the fact that they had consciously
115 perceived temporal order, meaning their temporal order threshold would have been shorter than 17ms.
116 These participants were therefore excluded from analysis. Reciprocally, we also excluded any
117 participant performing at or near chance when stimuli were separated by a 66ms SOAs, suggesting that
118 their temporal order threshold would have been longer than 66ms. In this way, we analysed TORT
119 performance only in those participants whose TOJ performance was at or near chance in the 17ms SOA
120 condition, and better than chance in the 66ms condition.

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

127 2.Experiment 1

128 2.1.Materials and methods

129 **2.1.1.Subjects**

130 Thirty-one healthy participants (mean age =26.5; SD = 5.3) volunteered for this experiment. They signed
131 written, informed consent forms, accepting to participate in the study, which had been approved by a
132 local ethics committee. They had normal or corrected-to-normal vision, were not colour-blind, and had
133 no reported neurological or cognitive disorders. After analysing their performance in the temporal order
134 judgment task (TOJ task), seven participants were excluded from the ANOVA analyses (6 participants
135 responded better than chance in the 17ms SOA condition and 1 participant responded at chance in the
136 66ms SOA condition). The final sample therefore comprised twenty-four participants, including sixteen
137 women and eight men (mean age = 26.2 years; SD = 4.6).

138 **2.1.2.Experimental tasks**

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

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

151 **2.1.2.1.Temporal order-cued RT (TORT) task**

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

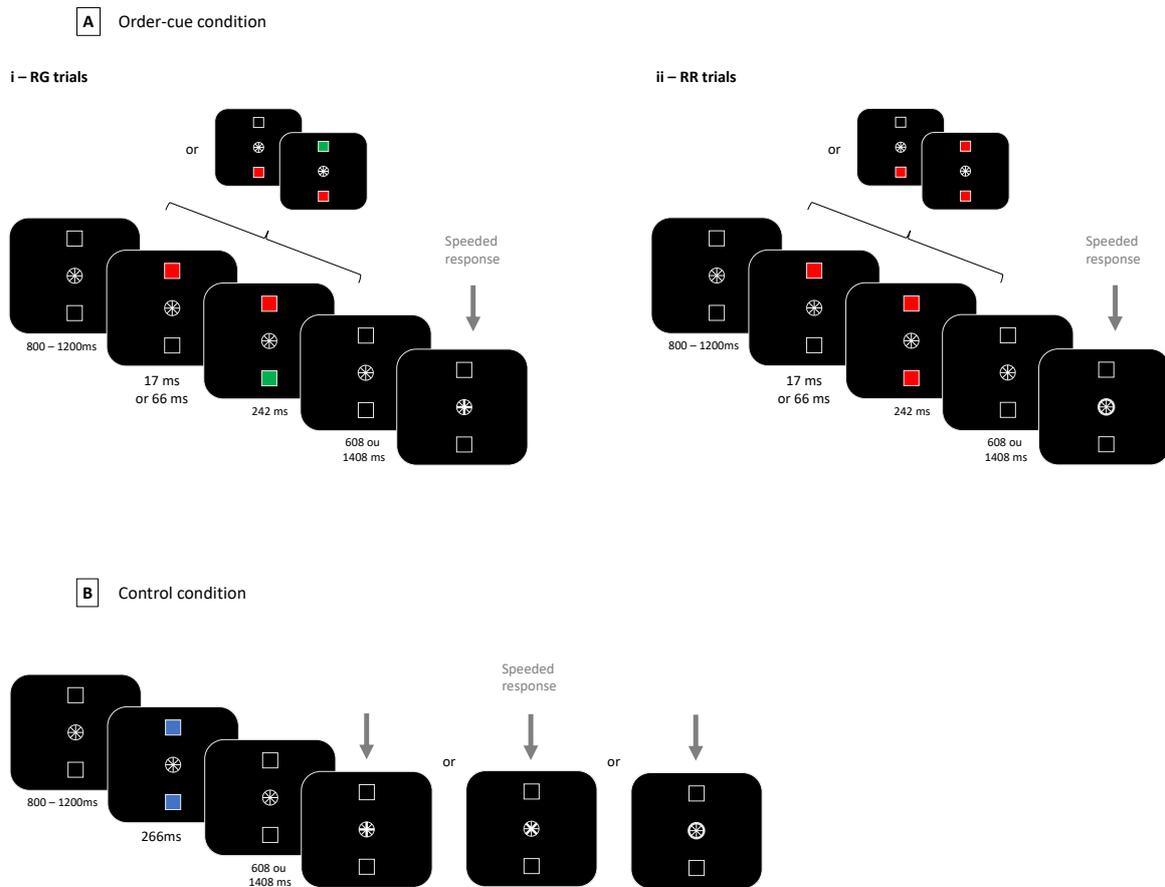
161 In all three conditions, a background image comprising two square frames, one above and one below
162 central fixation, was present throughout the task. The centres of the square frames were 12cm apart,
163 yielding a visual angle of about 10°. The central fixation point comprised a star surrounded by a circle.
164 All trials began with presentation of the cue. In the two order-cue conditions, the cue consisted of two
165 squares, coloured red or green, which were presented consecutively in a particular colour order (Figure
166 1Ai). The SOA between the onset of the first and second squares was 17ms in one block and 66ms in
167 the other block. Therefore, first square was presented for 17ms (or 66ms) before then being accompanied
168 by the second square. Both squares then remained on the screen for 242ms and disappeared

169 simultaneously. In the control condition, the cue consisted of simultaneous presentation of two blue
170 squares for 266ms (Figure 1B). After a variable interval of 608 or 1408ms, the target was presented on
171 the screen until the participant made their response (or for a maximum of 2 seconds if no response). The
172 target comprised one element of the central star that was highlighted to form one of three shapes: +, x,
173 or o (Figure 1). Participants were instructed to respond to the target as quickly as possible, using the
174 fingers of their right hand (index, middle or ring finger) according to the shape of the target (+, x, or o
175 respectively). Crucially, in the order-cue conditions, participants were told that the temporal order in
176 which the colours appeared could be used to predict the shape of the target. For example, if the red
177 square appeared first followed by green (RG trials) then the target would be a +. Conversely, if green
178 was presented first followed by red (GR trials) then the target would be an x. On the other hand, if the
179 two consecutive squares were both the same colour, either both red (RR trials) or both green (GG trials),
180 then the target would be an o. Participants could therefore use the temporal order information provided
181 by the cue to prepare the appropriate motor response and thus speed their RTs. In the control condition,
182 by contrast, participants were told that presentation of two blue squares would be simultaneous and
183 would hold no predictive information. Nevertheless, they were instructed still to respond as quickly as
184 possible to the shape of the target using the same finger associations as for the order-cue conditions
185 (index, middle or ring finger for +, x or o targets respectively). The computer recorded both accuracy
186 and speed of responses.

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

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

208



210

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

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

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

227

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

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

243 2.1.2.2. Temporal order judgment (TOJ) task

244 The TOJ task provided a direct measure of temporal order processing (Reingold & Merikle, 1988;
245 Schmidt & Vorberg, 2006), allowing us to verify whether SOAs of 17 and 66ms were likely to be below
246 or above, respectively, the temporal order threshold of our participants¹. The TOJ task was always
247 performed after the TORT task. We hypothesised that TOJ performance that was significantly better
248 than chance would reflect conscious perception of temporal order, indicating that stimuli were separated
249 by an SOA longer than the temporal order threshold. On the other hand, TOJ performance that was at
250 chance, or near-chance, levels could indicate that temporal order had not been consciously perceived
251 and so stimuli were separated by an SOA that was shorter than the temporal order threshold. Any
252 participants performing above chance for stimuli with a 17ms SOA, or below chance for those with an
253 66ms SOAs, were excluded from ANOVA analyses. To prevent priming of awareness (Lin & Murray,
254 2014) the 17ms and 66ms SOA conditions were tested in separate blocks. For a given participant, the
255 order of presentation of the 17ms or 66ms blocks was the same as that used in the TORT task. In order
256 to match our direct and indirect measures of temporal order processing as closely as possible (Reingold
257 & Merikle, 1988; Schmidt & Vorberg, 2006) the TOJ task used the same background image and cue
258 stimuli as the TORT task (see Figure 1Ai). Therefore, two coloured squares appeared consecutively in
259 a specific temporal order, either red then green (RG trials) or green then red (GR trials). The SOA
260 between the two coloured squares was either 17ms or 66ms. By contrast with the TORT task, there was
261 no subsequent target and instead participants had to judge the temporal order of the two colours by
262 indicating which of the colours appeared first. Again, to match the two tasks as closely as possible, they
263 used the same association between response finger and temporal order as in the TORT task. For example,
264 if a participant had been trained to respond to RG trials using their index finger in the TORT task, then
265 in the TOJ task they were asked to respond with their index finger if they perceived red first. For each
266 block (17ms or 66ms) participants were first familiarized with task instructions by performing 8 training
267 trials. They then performed 80 test trials, with 40 RG and 40 GR trials presented randomly. The
268 computer recorded discrimination accuracy.

269 2.1.3. Data analysis

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

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 \pm 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.

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

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

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

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

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

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

321 $Control\ RT = 0.5RT_{correct} + 0.5RT_{incorrect}$

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

324 $66msSOA\ RT = (\%TOJ_{correct})RT_{correct} + (\%TOJ_{incorrect})RT_{incorrect}$

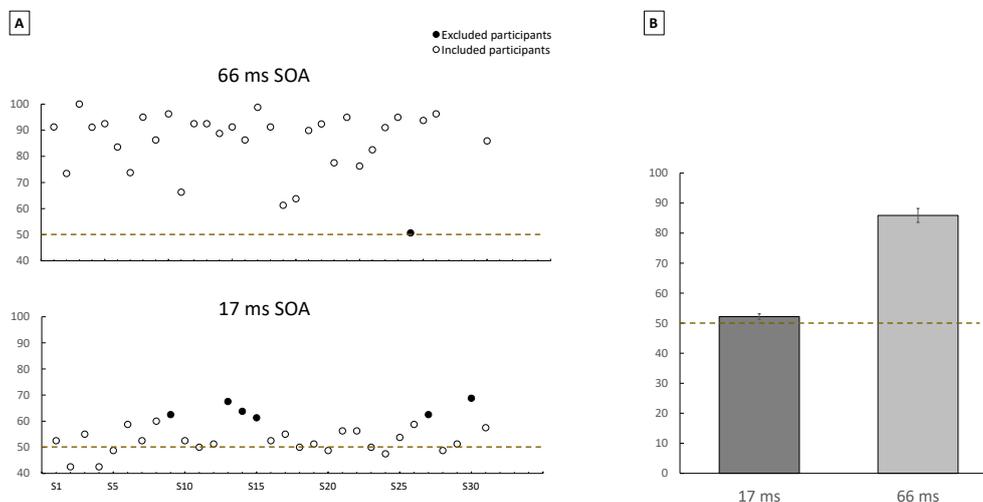
325 Using the observed average RT for the control and 66ms SOA conditions for each individual participant,
326 we can calculate $RT_{correct}$ and $RT_{incorrect}$. These values were then used, along with the participant's
327 average RT in the 17ms condition, to calculate the $\%TOJ_{correct}$ that would be predicted to result in that
328 17ms condition RT. The difference between modelled and observed $\%TOJ_{correct}$ was assessed with a
329 paired t-test.

330 2.2.Results

331 2.2.1.TOJ task:

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

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



347

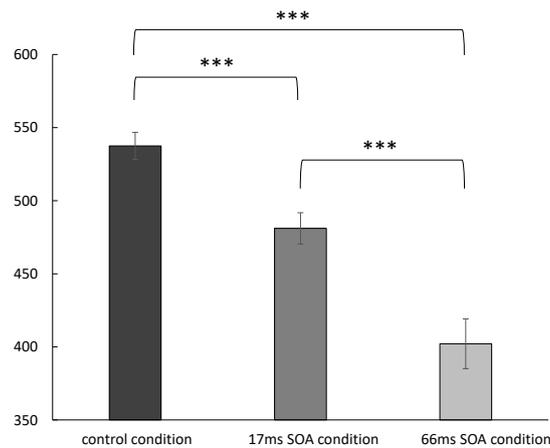
348 Figure 2 – A – Percentage of correct order judgments for each of the 31 participants in the TOJ task for the 66ms SOA condition
349 and the 17ms SOA condition. Black dots corresponded to the 7 participants excluded from the ANOVA analyses. B – Mean
350 percentage of correct order judgments for the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

352

353 2.2.2.TORT task:

354 To examine whether temporal order could be used to guide performance, we compared RTs in RG and
355 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
356 faster RTs for the order-cue conditions than the control condition (Figure 3), whether the cue stimuli
357 were separated by a 17ms SOA ($p < 0.0001$) or a 66ms SOA ($p < 0.0001$). In addition, RTs were faster for
358 the 66ms SOA condition than the 17ms SOA condition ($p < 0.0001$). There was a significant interaction
359 between cue and the order in which the 17ms or 66ms blocks were performed ($F_{2,44} = 6.721$; $p = 0.01$;
360 partial eta = 0.234), with the RT benefit for the 66ms condition being greater when the 66ms block was
361 performed second ($p < 0.0001$) rather than first ($p = 0.001$) whereas the RT benefit for the 17ms
362 condition was greater when it was performed first ($p < 0.0001$) rather than second ($p = 0.004$). There
363 was no main effect of block order ($F_{1,22} = 0.039$; $p = 0.846$; partial eta = 0.002).

365 One potential caveat to our findings is that the TORT task provides confirmation of the order-shape
366 association on every single trial: the order-cue is always followed by the target shape to which it is
367 associated (100% validity). Presentation of a particular shape in the TORT task could therefore confirm
368 (post-hoc) the order a participant thinks they might have seen. This trial-by-trial confirmation is not
369 present in the TOJ task. Although such post-hoc confirmation could not retrospectively modulate the
370 pre-target motor preparation processes necessary to speed RTs on a trial-by-trial basis, it might
371 disproportionately enhance temporal order processing in the TORT task over time. If so, we would
372 expect RTs to get progressively faster throughout the block as the participant overlearns the association
373 between order and shape. However, RTs did not show this pattern in either the 66ms condition or,
374 importantly, the 17ms one. To test this, RTs were grouped into four chronologically ordered time-bins
375 (i.e. trials 1-18; 19-36; 37-54; and 55-72) and a 2x4 repeated-measure ANOVA was conducted with
376 time-bin and cue (17 or 66ms) as within-subjects factors. Although there was a significant effect of time-
377 bin ($F_{3,69} = 4.897$, $p = 0.004$, partial eta = 0.176) RTs actually got *slower* over time for both the 66ms
378 condition (mean RT in time-bin 1-4 was 382ms; 399ms; 417ms; 407ms respectively) and 17ms
379 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
380 condition, and there was no interaction between cue and time-bin ($F_{3,69} = 0.267$, $p = 0.849$, partial eta =
381 0.011). Therefore, RT did not get faster over time, suggesting participants were not using trial-by-trial
382 confirmation of the cue-target association in the 17ms and 66ms conditions to improve temporal order
383 processing in the TORT task.
384



385

386 *Figure 3 - Mean RTs (N=24) for the 17ms SOA, 66ms SOA and control conditions of the TORT task. Participants RTs were*
 387 *significantly faster when target shape could be predicted by the temporal order of the squares' colour than when its shape*
 388 *could not be predicted in the control condition. Importantly, this effect was significant whether squares were separated by a*
 389 *subliminal (17ms) or supraliminal (66ms) SOA. Error bars represent SEM. *** = $p < 0.0001$*
 390

391 The analysis of accuracy (percentage correct) also revealed a significant main effect of cue ($F_{2,44} = 5.911$;
 392 $p = 0.013$; partial eta = 0.212). Planned pairwise comparisons indicated that participants were more
 393 accurate in the control condition (94.94%) than the order-cue conditions (91.9% for the 17ms SOA;
 394 92.2% for the 66ms SOA), whether the cue stimuli were separated by a 17ms SOA ($p = 0.014$) or a
 395 66ms SOA ($p = 0.001$). There was no significant difference between the 66ms and 17ms SOA conditions
 396 ($p > 0.5$). There was no significant effect of the order in which the 17ms or 66ms blocks were performed
 397 ($F_{1,22} = 0.517$; $p = 0.480$; partial eta = 0.023) nor interaction between cue and block order ($F_{2,44} = 0.959$;
 398 $p = 0.366$; partial eta = 0.042). Since accuracy was lower in the order-cue conditions, and RTs were
 399 faster (see above), this suggests the presence of a speed-accuracy trade-off. To investigate this further
 400 we conducted a correlation between the RT benefit of temporal order cues and the cost in accuracy
 401 induced by these order cues. The RT benefit per participant was calculated as $[(\text{meanRT}_{17\text{ms}} - \text{meanRT}_{\text{control}}) / \text{meanRT}_{\text{control}}]$ or $[(\text{meanRT}_{66\text{ms}} - \text{meanRT}_{\text{control}}) / \text{meanRT}_{\text{control}}]$ and the accuracy
 402 cost was calculated as $[(\text{mean}\% \text{correct}_{17\text{ms}} - \text{mean}\% \text{correct}_{\text{control}}) / \text{mean}\% \text{correct}_{\text{control}}]$ or
 403 $[(\text{mean}\% \text{correct}_{66\text{ms}} - \text{mean}\% \text{correct}_{\text{control}}) / \text{mean}\% \text{correct}_{\text{control}}]$. Across participants, there was
 404 a significant correlation between the RT benefit and the accuracy cost of temporal order cues, for the
 405 17ms SOA condition (Spearman $R = 0.441$; $p = 0.031$) though not for the 66ms SOA condition
 406 (Spearman $R = -0.237$; $p = 0.265$).
 407

408 An additional ANOVA was conducted to examine whether participants used the relative temporal order
 409 of *both* stimuli to guide performance, or whether they used only the first or second of the two consecutive
 410 stimuli. There was no significant main effect of shared colour ($F_{1,23} = 0.026$; $p = 0.873$; partial eta =
 411 0.001), indicating that participants used both stimuli to make their prediction rather than processing only
 412 the first or second. Mean RTs revealed that RTs were identical whether it was the first (mean RT =
 413 480.36ms for the 17ms SOA; mean RT = 403.75ms for the 66ms SOA) or the second (mean RT =
 414 482.18ms for the 17ms SOA; mean RT = 400.38ms for 66ms SOA) square that shared a colour with the
 415 repetitive RR/GG trials. There was a significant mean effect of SOA ($F_{1,23} = 53.348$; $p < 0.0001$; partial
 416 eta = 0.699), which simply replicated results of the previous ANOVA demonstrating that RTs were
 417 faster when stimuli were separated by 66ms (mean RT=402.1ms) than by 17ms (mean RT= 481.04ms).

418 There was no significant interaction between SOA and shared colour ($F_{1,23} = 0.254$; $p = 0.619$; partial
419 $\eta^2 = 0.011$), indicating that participants used both of the two squares to predict target shape whether the
420 temporal order of the two squares was consciously perceptible or not.

421 2.2.3. Modelling TOJ performance from TORT RTs:

422 For each of the original 31 participants, we calculated the TOJ accuracy score in the 17ms SOA
423 condition that would have been necessary to produce the RT observed in the 17ms condition of the
424 TORT task. The model predicted that, on average, participants would have had to report order correctly
425 on $66.2 \pm 2.3\%$ of trials in the TOJ task to obtain the RT that we observed in the TORT task. However,
426 participants, on average, reported order correctly on only $54.5 \pm 1.2\%$ of trials. In other words, the RT
427 effect we found in the TORT task was observed at a level of TOJ accuracy lower than that predicted by
428 the model. This effect was significant whether we tested the entire group of 31 participants ($t(30) = 5.66$;
429 $p < 0.0001$) or only the sample of 24 participants included in the ANOVAs ($t(23) = 5.15$; $p < 0.0001$).

430 2.3. Discussion

431 We used a novel paradigm (TORT task) to test whether the temporal order of two consecutive stimuli
432 could be used to predict the shape of a subsequent target, even when their order could not be consciously
433 perceived. The order of two coloured squares (red then green (RG), or vice versa (GR)) predicted target
434 shape, and RTs to detect the target were used as an indirect measure of temporal order processing.
435 Participants' ability to consciously perceive temporal order at SOAs of 17ms or 66ms was measured
436 directly in a separate TOJ task. We found that response times (RTs) in the TORT task were faster in the
437 66ms SOA order-cue condition compared to a non-predictive control condition, indicating that
438 participants were able to use consciously perceived order to predict target shape and so speed RTs.
439 Crucially, RT benefits were still present for the 17ms SOA order-cue condition compared to the control
440 condition. Since participants were performing near chance when stimuli were separated by a 17ms SOA
441 in the TOJ task, it is unlikely that this RT benefit was due to conscious perception of temporal order.
442 Instead, our results indicate that participants were able to use the cue to optimise performance even
443 though the temporal order of the two squares was not perceived consciously. However, the RT benefit
444 of the 17ms SOA cue was associated with a corresponding decrease in accuracy, suggesting these results
445 may be partially explained by a speed-accuracy trade-off. Indeed, speed-accuracy trade-offs have
446 already been reported for subconscious, as well as conscious, stimuli (Reuss et al., 2015). Of course,
447 RTs were measured in correct trials only and so the faster RTs in the order-cue conditions cannot simply
448 reflect the influence of fast, impulsive errors. In addition, participants responded correctly in the great
449 majority of trials (>90%) meaning that they weren't simply guessing. However, it's still possible that
450 participants may have adopted a general response strategy that prioritised speed over accuracy to a
451 greater extent in the 17ms condition than the control condition.

452 The TORT paradigm included trials in which the two consecutive stimuli were of the same colour
453 (RR/GG trials). These trials were included to encourage processing of both stimuli, rather than only one
454 or the other. This is important because prior simultaneity judgement experiments have shown that
455 participants preferentially process the second of two consecutively presented stimuli (Lalanne et al.,
456 2012; Poncelet & Giersch, 2015). However, in the current study we found that participants used both
457 stimuli to guide performance, showing no clear preference for processing one or the other. One of the
458 main experimental differences was that temporal order was defined by stimulus colour in our own
459 experiment (e.g. red then green), but by stimulus location (e.g. left then right) in previous experiments.
460 The discrepancy in results suggests that the reported processing bias for the second stimulus might be
461 present only when temporal order is defined in spatial terms. This hypothesis could be directly tested in

462 future experiments. More importantly however, the lack of processing bias for the first or second
463 stimulus in our own paradigm means that the experiment can now be repeated without the inclusion of
464 the RR/GG trials. This is important because their inclusion actually resulted in an unforeseen confound
465 that could potentially explain our pattern of results. The order-cue conditions and the control condition
466 were matched in terms of the number of response choices: both conditions comprised three response
467 choices for three possible targets. However, in the order-cue conditions, two different colours were
468 presented in the RG/GR trials but only one colour was presented in the RR/GG trials. This means that
469 if participants simply perceived that two different colours had been presented, whatever their temporal
470 order, they could eliminate the possibility that the target corresponding to the RR/GG cue would be
471 presented. Therefore, the number of possible targets, and so the number of possible response choices, in
472 the order-cue condition would actually be two rather than three. By contrast, in the control condition,
473 the cue is entirely non-predictive and so the number of possible targets, and therefore response choices,
474 is still three. The Hick-Hyman law states that the more response choices there are, the longer the
475 response time will be (Hick, 1952; Hyman, 1953). Since the number of response choices could be argued
476 to be smaller in the order-cue condition than the control condition, the faster responses observed in the
477 order-cue conditions could simply be explained by fewer response choices. To verify that our results
478 were due to temporal order processing and not just due to a difference in the number of response choices,
479 we conducted a second experiment similar in every respect to Experiment 1 except that we removed the
480 GG (or RR) trials in the order-cue condition and the third target colour in the control condition. This left
481 just two possible response choices in each condition. If we still observe faster responses in the order-
482 cue condition compared to the control condition at an SOA of 17ms, we can conclude that this effect is
483 not due to differences in the number of response choices but to subconscious temporal order processing.

484 3.Experiment 2

485 3.1.Materials and methods

486 3.1.1.Subjects

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

496 3.1.2.Experimental tasks

497 In this second experiment, stimuli in the TORT and TOJ task were identical to those used in Experiment
498 1 (Figure 1), except that trials including the target ‘o’ were removed.

499 3.1.2.1.Temporal order-cued RT (TORT) task

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

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

517 3.1.2.2.Temporal order judgment (TOJ) task

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

520 3.1.3.Data analysis

521 Statistical analyses were conducted with SPSS and R software and the threshold for significance was
522 set at $p < 0.05$ for all analyses. We repeated the same analyses as in Experiment 1. First, a χ^2 test was
523 performed on individual participant’s accuracy scores in the TOJ task. Of the 28 participants, four had

524 to be excluded, comprising three whose performance was significantly above chance for the 17ms
525 condition and one whose performance was near chance for the 66ms condition.

526 For the remaining sample of participants (n=24), we conducted 2x3 repeated-measures ANOVAs of
527 mean RTs and accuracy (%correct) in the GR and RG trials of the TORT task, with cue (17ms SOA,
528 66ms SOA, simultaneous control) as a within-subjects factor and SOA order (17ms then 66ms, 66ms
529 then 17ms) as a between-subjects factor. Very slow (>1000ms) or very fast RTs (<100ms) were first
530 excluded (0.81% of total trials) from both analyses and RTs corresponding to incorrect responses (6.83%
531 of total trials) were excluded from the RT analysis. Finally, as in Experiment 1, we modelled the level
532 of TOJ accuracy that would have been needed to produce the RT benefit observed in the 17ms SOA
533 condition for all 28 participants. The difference between modelled and observed %TOJcorrect was
534 assessed with a paired t-test.

535 3.2.Results

536 3.2.1.TOJ task:

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

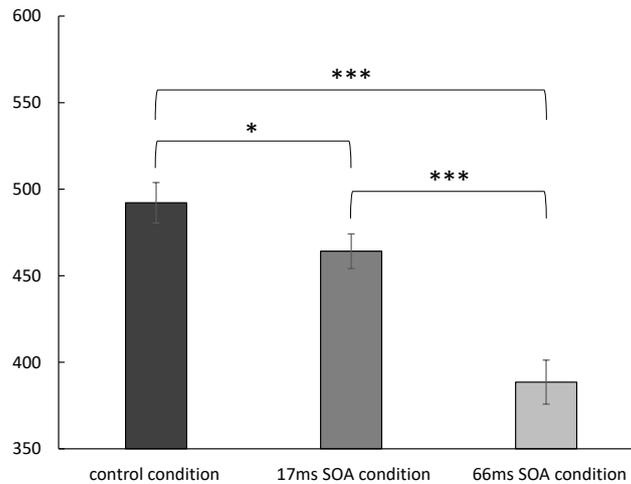
543 The remaining 24 participants judged the temporal order of two stimuli separated by a 17ms SOA near
544 chance level (mean = 51.2 %; SD = 4.8) and the order of stimuli separated by a 66ms SOA at a rate
545 considerably greater than chance (mean 85.3 %; SD = 9.69). This indicates that the 24 participants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

548 3.2.2.TORT task:

549 The ANOVA comparing RTs in the RG and GR order-cue trials to RTs in the control trials indicated a
550 significant effect of cue ($F_{2,44} = 41.780$; $p < 0.0001$; partial $\eta = 0.655$). Planned pairwise comparisons
551 indicated that participants had faster RTs for the order-cue conditions than the control condition (Figure
552 4). Importantly, this effect was significant whether the cue stimuli were separated by a 17ms SOA
553 ($p < 0.03$) or a 66ms SOA ($p < 0.0001$). In addition, RTs were faster for the 66ms SOA condition than the
554 17ms SOA condition ($p < 0.0001$). There was no significant interaction between cue and the order in
555 which the 17ms or 66ms blocks were performed ($F_{2,44} = 1.635$; $p = 0.207$; partial $\eta = 0.069$) and no
556 main effect of block order ($F_{1,22} = 0.595$; $p = 0.449$; partial $\eta = 0.026$).

557 As in the first experiment, we examined whether RTs got faster over time in the TORT task. A 2x4
558 repeated-measure ANOVA was conducted with time-bin and cue (17 or 66ms) as within-subject factors.
559 A significant effect of time ($F_{3,69} = 8.887$, $p < 0.001$, partial $\eta = 0.279$) again revealed that RTs got
560 slower over time in both the 66ms condition (mean RT in time-bin 1-4 was 352ms, 395ms, 400ms, and
561 408ms respectively) and the 17ms condition (mean RT 449ms, 457ms, 474ms, 474ms). An effect of cue
562 was observed ($F_{1,23} = 43,491$, $p < 0.001$, partial $\eta = 0.654$), simply confirming that RTs in the 66ms
563 condition were faster than those in the 17ms condition, and there was no interaction between cue and
564 time-bin ($F_{3,69} = 2.329$, $p = 0.082$, partial $\eta = 0.092$). Again, these results indicate that repeated

565 presentation of the cue-target association in the TORT task did not improve temporal order processing
566 over time.



567
568 *Figure 4 - Mean RTs (N=24) for the 17ms SOA, 66ms SOA and control conditions of the TORT task, when only two response*
569 *choices were possible. Participants RTs were significantly faster when target shape could be predicted by the temporal*
570 *order of stimulus colour than when its shape could not be predicted in the control condition. These effects were significant whether*
571 *stimuli were separated by a subliminal (17ms) or supraliminal (66ms) interval. Error bars are SEM. *** = $p < 0.0001$; * =*
572 *$0.01 < p < 0.05$*
573

574 The ANOVA of accuracy scores also revealed a significant main effect of cue ($F_{2,44} = 12.568$; $p < 0.001$;
575 partial $\eta^2 = 0.364$). Planned pairwise comparisons indicated that participants were more accurate in the
576 control condition (95.74%) than the order-cue conditions (91.16% for the 17ms SOA; 92.29% for the
577 66ms SOA), whether the cue stimuli were separated by a 17ms SOA ($p < 0.001$) or a 66ms SOA ($p =$
578 0.001). There was no significant difference between the 66ms and 17ms SOA conditions ($p > 0.5$). There
579 was no significant effect of the order in which the 17ms or 66ms blocks were performed ($F_{1,22} = 0.240$;
580 $p = 0.629$; partial $\eta^2 = 0.011$) nor interaction between cue and block order ($F_{2,44} = 0.447$; $p = 0.642$;
581 partial $\eta^2 = 0.020$). As in Experiment 1, we conducted a correlation between the RT benefit and the
582 accuracy cost of temporal order cues. Across participants, there was no significant correlation between
583 the RT benefit and the accuracy cost, either for the 17ms SOA condition (Spearman $R = 0.127$; $p =$
584 0.554) or the 66ms SOA condition (Spearman $R = 0.030$; $p = 0.888$). In other words, the participants
585 whose RTs were speeded by the provision of temporal order cues were not the same as those whose
586 accuracy was impaired.

587

588 3.2.3. Modelling TOJ performance from TORT RTs:

589 Our model predicted that, on average, participants would have had to report order correctly on
590 $61.4 \pm 3.2\%$ of trials in the 17ms condition of the TOJ task to obtain the RT we observed in the 17ms
591 condition of the TORT task. However, participants, on average, reported order correctly on only
592 $52.8 \pm 1.2\%$ of trials. Crucially, the observed TOJ performance was significantly lower than predicted
593 performance, whether we tested the entire group of 28 participants ($t(27) = 2.25$; $p = 0.033$) or only the
594 24 participants included in the ANOVAs ($t(23) = 2.56$; $p = 0.0175$).

595 3.3.Discussion

596 We found the same RT pattern as in the first experiment, with responses to the target being faster in the
597 66ms and 17ms SOA order-cue conditions than the control condition. By more carefully matching the
598 number of response choices between the control condition and the order-cue conditions in this
599 experiment (by eliminating the ‘o’ target trials in all conditions), we therefore confirmed that the faster
600 responses in the 17ms SOA order-cue condition compared to the control condition in Experiment 1 was
601 not just due to a difference in response choices across conditions. However, it is interesting to note that
602 the difference in RTs for the 17ms SOA condition compared to the control condition is smaller in this
603 experiment than in the first experiment (RT gain of 56.4 ms for Experiment 1; 28 ms for Experiment 2).
604 This indicates that a part of the RT gain observed in the first experiment may indeed have been due to
605 differences in the number of response choices between conditions. Nevertheless, the fact that RTs were
606 still significantly faster in the 17ms SOA condition compared to the control condition in Experiment 2
607 confirms that temporal order was processed subconsciously and helped guide behaviour.

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

617

618 4. General Discussion

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

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

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

647 There is a clear distinction between neural processing of information on the one hand and being
648 conscious of this processing, or of the stimuli conveying that information, on the other. Many cognitive
649 processes are performed without being consciously aware of them (Kouider & Dehaene, 2007; Velmans,
650 1991). For example, the hemianopic patient DB could correctly discriminate stimuli presented in his
651 blind field even though he did not consciously perceive them (Weiskrantz et al., 1974). The phenomenon
652 of blindsight (Ajina & Bridge, 2017; Boyer et al., 2005; Weiskrantz et al., 1974), or the effects of masked
653 priming (Dehaene et al., 1998; Del Cul et al., 2007; Kouider & Dehaene, 2007; Pesciarelli et al., 2019),
654 illustrate how visual stimuli can be processed even though they have not been consciously perceived.
655 Herzog, Kammer, & Scharnowski (2016) have proposed a two-stage model in which visual information
656 is first processed subconsciously before then being integrated into a conscious perception. More
657 interestingly, they suggest that subconscious processing has a higher temporal resolution than conscious
658 perception (see also Giersch, Lalanne, Van Assche, & Elliott, 2013; Lalanne et al., 2012; Poncelet &
659 Giersch, 2015). Our own results support this two-stage model, with stimuli separated by a 17ms SOA
660 being subconsciously processed in the TORT task but not consciously perceived in the TOJ task.
661 Moreover, stimulus order was processed sufficiently well to be able to improve subsequent motor
662 responding to targets in the TORT task. Nevertheless, we found that the RT benefit was significantly

663 greater in the 66ms SOA condition than the 17ms SOA condition. This means participants were better
664 able to use the temporal order of two consecutive stimuli to predict target identity when it was
665 consciously perceived. Therefore, even though action can be modulated by subconscious processing,
666 conscious control nevertheless further modulates performance. In our case, we hypothesise that
667 subconscious temporal order processing drives initiation of the motor response, whether stimuli were
668 consciously perceptible or not. Conscious perception of temporal order might then influence subsequent
669 stages of motor programming so as to improve performance even more.

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

684 We imposed the constraint that participants had to be able to consciously perceive the temporal order of
685 the two cue stimuli in the 66ms condition of the TOJ task, but *not* to consciously perceive their order in
686 the 17ms condition. Nevertheless, 11 participants out of 59 (seven participants from the original sample
687 of 31 volunteers for Experiments 1 and four participants from the original sample of 28 volunteers in
688 Experiment 2) (i.e. 20%) had to be excluded because of above-chance performance in the 17ms SOA
689 condition, or below-chance performance in the 66ms SOA condition. This implies a considerable degree
690 of variability in temporal order thresholds between participants. There is a burgeoning literature
691 indicating that individual differences in temporal order thresholds could be explained by individual
692 differences in the frequency of neural oscillations, specifically the alpha rhythm. For example, there is
693 a significant correlation between occipital alpha rhythm and the fusion threshold of two consecutive
694 events: the higher the alpha frequency the better the participants’ temporal resolution (Samaha & Postle,
695 2015). In the future, it would be informative to measure alpha rhythms during performance of the TOJ
696 task to determine whether alpha frequency could predict whether or not the temporal order of two stimuli
697 separated by e.g. 17ms is consciously perceptible or not.

698 5.Acknowledgments

699 This work was funded by an Agence National de Recherche grant (ANR-16-CE37-0004-02) awarded
700 to JTC and AG.

701 6.Bibliography

- 702 Ajina, S., & Bridge, H. (2017). Blindsight and Unconscious Vision: What They Teach Us about the
703 Human Visual System. *The Neuroscientist*, 23(5), 529–541.
704 <https://doi.org/10.1177/1073858416673817>
- 705 Boyer, J. L., Harrison, S., & Ro, T. (2005). Unconscious processing of orientation and color without
706 primary visual cortex. *Proceedings of the National Academy of Sciences of the United States of*
707 *America*, 102(46), 16875–16879. <https://doi.org/10.1073/pnas.0505332102>
- 708 Capa, R. L., Duval, C. Z., Blaison, D., & Giersch, A. (2014). Patients with schizophrenia selectively
709 impaired in temporal order judgments. *Schizophrenia Research*, 156(1), 51–55.
710 <https://doi.org/10.1016/j.schres.2014.04.001>
- 711 Cass, J., & Van der Burg, E. (2014). Remote temporal camouflage: Contextual flicker disrupts
712 perceived visual temporal order. *Vision Research*, 103, 92–100.
713 <https://doi.org/https://doi.org/10.1016/j.visres.2014.08.008>
- 714 Cass, J., & Van der Burg, E. (2019). Dynamic distractor environments reveal classic visual field
715 anisotropies for judgments of temporal order. *Attention, Perception, & Psychophysics*, 81(3),
716 738–751. <https://doi.org/10.3758/s13414-018-1628-2>
- 717 Cecere, R., Rees, G., & Romei, V. (2015). Individual differences in alpha frequency drive crossmodal
718 illusory perception. *Current Biology*, 25(2), 231–235. <https://doi.org/10.1016/j.cub.2014.11.034>
- 719 Dehaene, S., Naccache, L., Le Clec'H, G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., van de
720 Moortele, P.-F., & Le Bihan, D. (1998). Imaging unconscious semantic priming. *Nature*,
721 395(6702), 597–600. <https://doi.org/10.1038/26967>
- 722 Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain Dynamics Underlying the Nonlinear Threshold for
723 Access to Consciousness. *PLOS Biology*, 5(10), e260.
724 <https://doi.org/10.1371/journal.pbio.0050260>
- 725 Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia:
726 A review. *Psychonomic Bulletin & Review*, 2(4), 460–493. <https://doi.org/10.3758/BF03210983>
- 727 Fink, M., Ulbrich, P., Churan, J., & Wittmann, M. (2006). Stimulus-dependent processing of temporal
728 order. *Behavioural Processes*, 71(2–3), 344–352.
729 <https://doi.org/https://doi.org/10.1016/j.beproc.2005.12.007>
- 730 Franck, N., Posada, A., Pichon, S., & Haggard, P. (2005). Altered subjective time of events in
731 schizophrenia. *The Journal of Nervous and Mental Disease*, 193(5), 350–353.
732 <https://doi.org/10.1097/01.nmd.0000161699.76032.09>
- 733 Gepshtein, S., & Kubovy, M. (2007). The lawful perception of apparent motion. *Journal of Vision*, 7(8),
734 9. <https://doi.org/10.1167/7.8.9>
- 735 Giersch, A., Lalanne, L., Van Assche, M., & Elliott, M. (2013). On Disturbed Time Continuity in
736 Schizophrenia: An Elementary Impairment in Visual Perception? *Frontiers in Psychology*, 4, 281.
737 <https://doi.org/https://doi.org/10.3389/fpsyg.2013.00281>

- 738 Herzog, M. H., Kammer, T., & Scharnowski, F. (2016). Time Slices: What Is the Duration of a Percept?
739 *PLOS Biology*, 14(4), e1002433. <https://doi.org/10.1371/journal.pbio.1002433>
- 740 Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*,
741 4(1), 11–26. <https://doi.org/10.1080/17470215208416600>
- 742 Hirsh, I. J. (1959). Auditory perception of temporal order. *The Journal of the Acoustical Society of*
743 *America*, 31(6), 759–767. <https://doi.org/10.1121/1.1907782>
- 744 Hirsh, I. J., & Sherrick Jr, C. E. (1961). Perceived order in different sense modalities. *Journal of*
745 *Experimental Psychology*, 62(5), 423–432. <http://dx.doi.org/10.1037/h0045283>
- 746 Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental*
747 *Psychology*, 45(3), 188–196. <https://doi.org/10.1037/h0056940>
- 748 Jaśkowski, P., & Rusiak, P. (2008). Temporal order judgment in dyslexia. *Psychological Research*,
749 72(1), 65–73. <https://doi.org/10.1007/s00426-006-0093-z>
- 750 Kanabus, M., Szelag, E., Rojek, E., & Poppel, E. (2002). Temporal order judgement for auditory and
751 visual stimuli. *Acta Neurobiologiae Experimentalis*, 62(4), 263–270.
- 752 Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: a critical
753 review of visual masking. *Philosophical Transactions of the Royal Society B: Biological Sciences*,
754 362(1481), 857–875. <https://doi.org/10.1098/rstb.2007.2093>
- 755 Lalanne, L., Van Assche, M., Wang, W., & Giersch, A. (2012). Looking forward: an impaired ability in
756 patients with schizophrenia? *Neuropsychologia*, 50(12), 2736–2744.
757 <https://doi.org/10.1016/j.neuropsychologia.2012.07.023>
- 758 Lin, Z., & Murray, S. O. (2014). Priming of awareness or how not to measure visual awareness. *Journal*
759 *of Vision*, 14(1), 27. <https://doi.org/10.1167/14.1.27>
- 760 McFarland, D. J., Cacace, A. T., & Setzen, G. (1998). Temporal-Order Discrimination for Selected
761 Auditory and Visual Stimulus Dimensions. *Journal of Speech, Language, and Hearing Research*,
762 41(2), 300–314. <https://doi.org/10.1044/jslhr.4102.300>
- 763 Milton, A., & Pleydell-Pearce, C. W. (2016). The phase of pre-stimulus alpha oscillations influences
764 the visual perception of stimulus timing. *Neuroimage*, 133, 53–61.
765 <https://doi.org/10.1016/j.neuroimage.2016.02.065>
- 766 Naveh-Benjamin, M. (1990). Coding of temporal order information: An automatic process? *Journal of*
767 *Experimental Psychology: Learning, Memory, and Cognition*, 16(1), 117–126.
768 <https://doi.org/10.1037/0278-7393.16.1.117>
- 769 Ortiz, R., Estévez, A., Muñeton, M., & Domínguez, C. (2014). Visual and auditory perception in
770 preschool children at risk for dyslexia. *Research in Developmental Disabilities*, 35(11), 2673–
771 2680. <https://doi.org/10.1016/j.ridd.2014.07.007>
- 772 Pastore, R. E., & Farrington, S. M. (1996). Measuring the difference limen for identification of order
773 of onset for complex auditory stimuli. *Perception & Psychophysics*, 58(4), 510–526.
774 <https://doi.org/10.3758/BF03213087>
- 775 Pesciarelli, F., Scorolli, C., & Cacciari, C. (2019). Neural correlates of the implicit processing of
776 grammatical and stereotypical gender violations: A masked and unmasked priming study.
777 *Biological Psychology*, 146, 107714.
778 <https://doi.org/https://doi.org/10.1016/j.biopsycho.2019.06.002>
- 779 Poncelet, P. E., & Giersch, A. (2015). Tracking Visual Events in Time in the Absence of Time

- 780 Perception: Implicit Processing at the ms Level. *PLOS ONE*, 10(6), e0127106.
781 <https://doi.org/10.1371/journal.pone.0127106>
- 782 Pöppel, E. (1970). Excitability cycles in central intermittency. *Psychologische Forschung*, 34(1), 1–9.
783 <https://doi.org/10.1007/BF00422860>
- 784 Pöppel, E. (1997). A hierarchical model of temporal perception. *Trends in Cognitive Sciences*, 1(2),
785 56–61. [https://doi.org/10.1016/S1364-6613\(97\)01008-5](https://doi.org/10.1016/S1364-6613(97)01008-5)
- 786 Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.),
787 *Information Processing and Cognition: The Loyola Symposium* (pp. 55–85). Lawrence Erlbaum.
- 788 Reingold, E. M., & Merikle, P. M. (1988). Using direct and indirect measures to study perception
789 without awareness. *Perception & Psychophysics*, 44(6), 563–575.
790 <https://doi.org/10.3758/BF03207490>
- 791 Repp, B. H. (2000a). Compensation for subliminal timing perturbations in perceptual-motor
792 synchronization. *Psychological Research*, 63(2), 106–128. <https://doi.org/10.1007/PL00008170>
- 793 Repp, B. H. (2000b). Subliminal temporal discrimination revealed in sensorimotor coordination.
794 *Rhythm Perception and Production*, 129–142.
- 795 Reuss, H., Kiesel, A., & Kunde, W. (2015). Adjustments of response speed and accuracy to
796 unconscious cues. *Cognition*, 134, 57–62.
797 <https://doi.org/https://doi.org/10.1016/j.cognition.2014.09.005>
- 798 Riemer, M. (2018). Delusions of control in schizophrenia: Resistant to the mind’s best trick?
799 *Schizophrenia Research*, 197, 98–103.
800 <https://doi.org/https://doi.org/10.1016/j.schres.2017.11.032>
- 801 Samaha, J., & Postle, B. R. (2015). The speed of alpha-band oscillations predicts the temporal
802 resolution of visual perception. *Current Biology*, 25(22), 2985–2990.
803 <https://doi.org/10.1016/j.cub.2015.10.007>
- 804 Schmidt, T., & Vorberg, D. (2006). Criteria for unconscious cognition: Three types of dissociation.
805 *Perception & Psychophysics*, 68(3), 489–504. <https://doi.org/10.3758/BF03193692>
- 806 Schwartz, B. L., Deutsch, L. H., Cohen, C., Warden, D., & Deutsch, S. I. (1991). Memory for temporal
807 order in schizophrenia. *Biological Psychiatry*, 29(4), 329–339. [https://doi.org/10.1016/0006-3223\(91\)90218-B](https://doi.org/10.1016/0006-3223(91)90218-B)
- 809 Shanks, D. R. (2017). Regressive research: The pitfalls of post hoc data selection in the study of
810 unconscious mental processes. *Psychonomic Bulletin & Review*, 24(3), 752–775.
811 <https://doi.org/10.3758/s13423-016-1170-y>
- 812 Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*,
813 81(1), 174–176. <https://doi.org/10.1037/h0027448>
- 814 Spence, C., Baddeley, R., Zampini, M., James, R., & Shore, D. I. (2003). Multisensory temporal order
815 judgments: When two locations are better than one. *Perception & Psychophysics*, 65(2), 318–
816 328. <https://doi.org/10.3758/BF03194803>
- 817 Strybel, T. Z., Manligas, C. L., Chan, O., & Perrott, D. R. (1990). A comparison of the effects of spatial
818 separation on apparent motion in the auditory and visual modalities. *Perception &*
819 *Psychophysics*, 47(5), 439–448. <https://doi.org/10.3758/BF03208177>
- 820 Van der Burg, E., Alais, D., & Cass, J. (2018). Rapid recalibration to audiovisual asynchrony follows the
821 physical—not the perceived—temporal order. *Attention, Perception, & Psychophysics*, 80(8),

- 822 2060–2068. <https://doi.org/10.3758/s13414-018-1540-9>
- 823 VanRullen, R. (2016). Perceptual cycles. *Trends in Cognitive Sciences*, *20*(10), 723–735.
824 <https://doi.org/10.1016/j.tics.2016.07.006>
- 825 Varela, F. J., Toro, A., John, E. R., & Schwartz, E. L. (1981). Perceptual framing and cortical alpha
826 rhythm. *Neuropsychologia*, *19*(5), 675–686. [https://doi.org/10.1016/0028-3932\(81\)90005-1](https://doi.org/10.1016/0028-3932(81)90005-1)
- 827 Velmans, M. (1991). Is human information processing conscious? *Behavioral and Brain Sciences*,
828 *14*(4), 651–669. <https://doi.org/10.1017/S0140525X00071776>
- 829 Weiskrantz, L., Warrington, Elizabeth, K., Sanders, M., D., & Marshall, J. (1974). Visual Capacity in the
830 Hemianopic Field Following a Restricted Occipital Ablation. *Brain*, *97*(1), 709–728.
831 <https://doi.org/10.1093/brain/97.1.709>
- 832 Wittmann, M. (1999). Time perception and temporal processing levels of the brain. *Chronobiology*
833 *International*, *16*(1), 17–32. <https://doi.org/10.3109/07420529908998709>
- 834 Wittmann, M. (2011). Moments in time. *Frontiers in Integrative Neuroscience*, *5*, 66.
835 <https://doi.org/10.3389/fnint.2011.00066>
- 836 Wutz, A., Melcher, D., & Samaha, J. (2018). Frequency modulation of neural oscillations according to
837 visual task demands. *Proceedings of the National Academy of Sciences*, *115*(6), 1346–1351.
838 <https://doi.org/10.1073/pnas.1713318115>
- 839