

1
2
3
4
5
6
7
8
9
10
11
12

**Exploring the role of overt attention allocation during time estimation: an eye-
movement study**

Ruth S Ogden¹, Frederieke Turner¹ & Ralph Pawling¹

¹School of Psychology, Liverpool John Moores University, Liverpool, UK

13 Abstract

14 Cognitive models of time perception propose that perceived duration is influenced by
15 how quickly attention is orientated to the to-be-timed event and how consistently attention is
16 sustained on the to-be-timed event throughout its presentation. Insufficient attention to time is
17 therefore associated with shorter more variable representations of duration. However, these
18 models do not specify whether covert or overt attentional systems are primarily responsible for
19 paying attention during timing. The current study sought to establish the role of overt attention
20 allocation during timing by examining the relationship between eye-movements and perceived
21 duration. Participants completed a modified spatial cueing task in which they estimated the
22 duration of short (1400ms) and long (2100 ms) validly and invalidly cued targets. Time to first
23 fixation and dwell time were recorded throughout. The results showed no significant
24 relationship between overt sustained attention and mean duration estimates. Reductions in
25 overt sustained attention were however associated with increases in estimate variability for the
26 long target duration. Overt attention orientation latency was predictive of the difference in the
27 perceived duration of validly an invalidly cued short targets but not long ones. The results
28 suggest that overt attention allocation may have limited impact on perceived duration.

29

30 Introduction

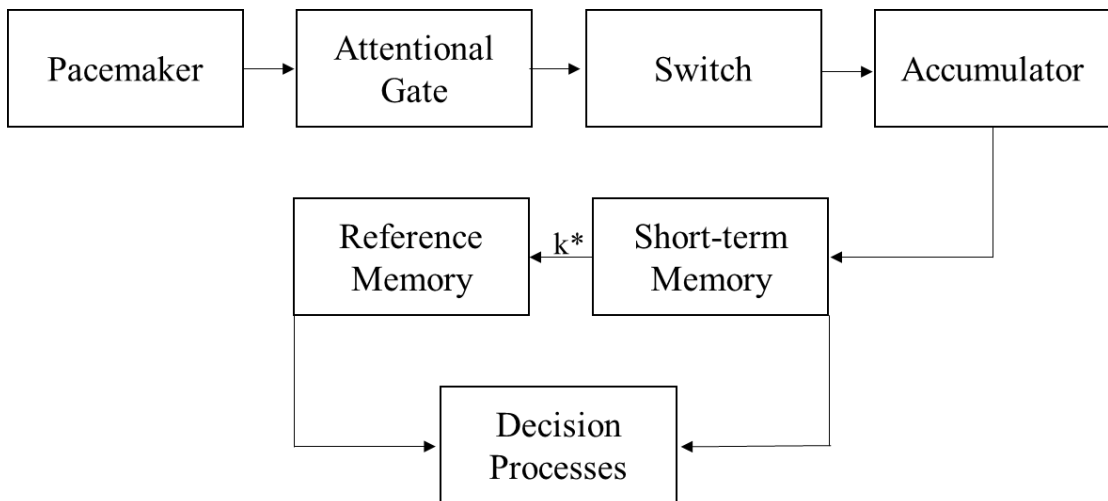
31 The ability to accurately judge the duration of events is dependent on a broad range of
32 cognitive resources including attention. Cognitive models of time perception, such as Scalar
33 Expectancy Theory (SET) (Gibbon, Church & Meck, 1984) and the Attentional Gate Model of
34 timing (AGM) (Block & Zakay, 1996; Zakay & Block, 1995, 1996), provide theoretical
35 accounts of how attention allocation influences perceived duration. SET proposes that time is
36 processed by a pacemaker-accumulator clock connected by a switch. At the start of a to-be-
37 timed-event, the switch between the pacemaker and the accumulator closes allowing output
38 from the pacemaker to be transferred to the accumulator. At the end of the to-be-timed-event
39 the switch opens and accumulation ceases. The amount of output accumulated forms the
40 representation of duration. Increases in switch closure latency therefore delay the
41 commencement of accumulation, resulting in less accumulation and a shorter estimate of
42 duration. The switch is often considered to be a form of *selective attention* to time, with changes
43 in switch latency being thought to reflect changes in the speed with which attention is orientated
44 towards the to-be-timed-stimulus. It is unclear however whether the switch represents a form
45 of overt or covert attentional processing.

46 The AGM formalised the role of attention in timing by adding an attentional gate to the
47 SET framework (see Figure 1). Although the precise nature of the gate remains debated (see
48 Lejeune, 1998, 2000 and Zakay, 2000 for discussion), it is now widely accepted that the
49 attentional gate is able to open and close throughout the presentation of a to-be-timed-stimulus
50 and therefore reflects *sustained attention* to the timed event. When attention to time (or the to-
51 be-timed-stimulus) decreases the gate opens and accumulation is reduced resulting in a
52 shortening of perceived duration and more variable representations of duration. Increases in
53 attention to time result in greater closing of the gate, more accumulation and a longer, less
54 variable representations of duration. The AGM also provided clearer specification for the
55 attentional role of the switch in timing. Here, the switch is responsible for the detection of
56 relevant stimuli and in doing so, commences the start of the accumulation process. As in SET,
57 this reflects the orientation of attention to the to-be-timed-event. Therefore, increased latency
58 in switch closure reduces accumulation, resulting in a shorter representation of duration
59 whereas decreases in switch latency result in more accumulation and a longer representation
60 of duration. Although not central to this manuscript, it is interesting to note that in the AGM
61 the switch is positioned after the gate. This seems perhaps paradoxical in that orientation and
62 evaluation of the stimulus (switch) occurs after sustaining attention on the to-be-time-event

63 (gate). Like SET however, the AGM does not specify whether the gate or the switch operate
64 as a function of overt or covert attentional processing.

65 Switch (selective attention orientation) and gate (sustained attention) effects are often
66 distinguished by the effects that they have on perceived duration (see Wearden et al., 2010, and
67 Matthews & Meck, 2016 for discussion). Switch latency effects are thought to be absolute,
68 having the same effect on the perceived duration of stimuli of different durations. Gate effects
69 however reflect sustained attention to time throughout a stimulus and are therefore
70 multiplicative in nature having greater effects with longer stimulus durations (see Buhusi &
71 Meck, 2009, Coull, Vidal, Nazarian, & Macar, 2004 for discussion).

72 Figure 1: A modified schematic of the AGM adapted from Zakay & Block (1995).



73

74 The primary prediction of SET and the AGM, that reduced focus of attention on time
75 results in shorter more variable representations of time, is supported by experimental studies.
76 Consistent with the proposed role of the attentional gate, dual-task studies consistently show
77 that estimates of time are shorter and more variable under dual-task than single task conditions
78 (see Block, Hancock & Zakay, 2010 for review). This is thought to be because attention
79 allocated to the completion of the concurrent non-timing task results in greater gate opening
80 under dual than single-task conditions, resulting in shorter more variable representations of
81 duration. Further support comes from studies in which participants are instructed to increase
82 or decrease the amount of attention they pay to time. For example, Steinborn, Langer &
83 Huestegge (2017) showed that simply instructing participants to sustain focus removed natural
84 fluctuations in attention and the associated increases in response variability.

85 The findings of spatial cueing studies are consistent with the proposed operation of the
86 switch in SET and the AGM. Studies show that the perceived duration of to-be-timed events
87 are lengthened when they appear in a location preceded by a valid exogenous (Seifried &
88 Ulrich, 2011; Yershurun & Marom, 2008) or endogenous spatial cue (Enns, Brehaut & Marom,
89 2008; Mattes & Ulrich, 1998). Conversely, invalid exogenous or endogenous spatial cues
90 subjectively shorten the perceived duration of subsequent events relative to valid cues (Enns,
91 Brehaut & Marom, 2008; Mattes & Ulrich, 1998; Seifried & Ulrich, 2011; Yershurun &
92 Marom, 2008). However, whilst the effects of spatial cues are broadly consistent, it should be
93 noted that the reverse effects were observed by Chen & O’Neill (2002), although further
94 examination by Seifried & Ulrich (2011) suggested that unique experimental conditions in
95 Chen & O’Neill (2002) led to this finding.

96 Studies of typically and atypically developing individuals also suggest that reduced
97 attentional capacity increases the variability of duration representations. Developmental
98 differences in the attentional capacities of young children, older children and adults are also
99 thought to contribute to greater variability in the timing of young children (see Droit-Volet,
100 2003, 2016). Similarly, in clinical groups such as autistic spectrum disorders (ASD), reduced
101 sensitivity to time (increased time variability) has been observed in some studies (e.g. Allman
102 & Falter, 2015; Isaksson, Salomaki, Tuominen, Arstila, Falter-Wagner & Noreika, 2018; Vogel
103 Falter-Wagner, Schoofs, Kramer, Kupke & Vogeley, 2019). However, when ASD and control
104 participants are matched for cognitive function, no differences in timing are observed
105 suggesting that differences in attention and working memory may contribute to these effects
106 when observed (Gil, Chambres, Hyvert, Fanget & Droit-Volet, 2012). Attentional differences
107 are also thought to contribute towards impaired temporal sensitivity in people with attention
108 deficit hyperactivity disorder (ADHD) in comparison with controls (e.g. Smith, Taylor, Rogers,
109 Newman & Rubia, 2002; Noreika, Falter & Rubia, 2013). Although collectively these studies
110 offer support for an effect of attention on timing, it is not always clear whether these effects
111 are attributed to the operation of the gate, the switch or a combination of the two, or whether
112 they are due to differences in covert attentional capabilities or over attentional differences.

113 Although current findings from experimental and individual differences studies support
114 the SET and the AGM’s proposed roles of attention in timing there are significant gaps in our
115 understanding of precisely how attention functions during timing. Most importantly perhaps,
116 both SET and the AGM are agnostic about whether timing is accomplished through overt or
117 covert attentional processing systems. Overt attention in the visual domain refers to shifts in

118 attention that involve head or eye movements, whereas covert attention refers to shifts in
119 attentional in the absence of eye or head movement (Posner, 1980). One possibility is that
120 accurate time perception can be achieved solely through covertly attending to the to-be-timed
121 event in the periphery. Here, switch closure and opening would be prompted by shifts in
122 attention which occurred in the absence of eye-movements, or at least in the absence of eye-
123 movements resulting in foveation of the to-be-timed stimulus. Similarly, gate opening and
124 closure would be governed by sustained covert attention on the to-be-timed stimulus in the
125 absence of sustained fixation in the fovea. However, another possibility is that accurate timing
126 is only possible when attention is overtly focused on the to-be-timed event. In this overt
127 attention scenario, for the switch to close and open and for the attentional gate to remain closed,
128 the to-be-timed stimulus would need to be foveated throughout presentation. A further
129 possibility however is that the switch and the gate may be controlled by different attentional
130 processes, for example, covert attention may identify a to-be-timed target, resulting in switch
131 closure. However, this may result in a shift in overt attention to the target resulting in overt
132 control of the attentional gate. The converse is also possible; overt attention may be needed to
133 close the switch, but then covert attention can be used to monitor the to-be-timed event
134 throughout its presentation.

135 The lack of specificity regarding the influence of overt and covert attention is
136 compounded by the fact that previous studies into the role of attention in timing have often
137 failed to take objective measures of attention allocation during timing to evidence their
138 suggestions. As a result, simple questions such as “does how long something is overtly looked
139 at correlate with its perceived duration?” remain difficult to conclusively answer. These issues
140 have led to suggestions that objective measures of overt and covert attention should be used to
141 demonstrate the precise roles and mechanisms of attention allocation in timing (see Matthews
142 & Meck, 2016; Ogden, Turner & Pawling, 2020; Wearden, 2016 for discussion).

143 One way to integrate objective attention measures of overt attention into timing studies
144 is through the measurement of eye movements. Even though attention and oculomotor systems
145 are traditionally considered as separate modules, even covert attentional shifts appear to
146 involve the oculomotor system to some degree (e.g de Haan et al., 2008; Van der Stigchel &
147 Theeuwes, 2007). Overt attentional shifts at their most basic level can be measured by tracking
148 changes in foveation, which is possible through the use of eye-tracking technology (Kulke et
149 al., 2016; Wang et al., 2019). In typical studies Eye-tracking has been widely used to record
150 changes in endogenous and exogenous overt attention allocation (Parkhurst, Law & Niebur,

151 2002, Soto, Heinke, Humphreys, & Blanco, 2005, Theeuwes, Kramer, Hahn, Irwin, &
152 Zelinsky, 1999 and see Eckstein, Guerra-Carrillo, Singley, & Bunge, 2017 and Rayner, 2009
153 for reviews). Simple and elegant spatial cuing tasks, perhaps the best known of which is the
154 Posner paradigm (Posner, 1980), have been used for decades to explore attention capture,
155 including overt exogenous attentional shifts. The Posner paradigm typically involves a
156 participant fixating on a central location after which a cue, often a dot, flash or geometric shape
157 appears at a peripheral location, followed by a target (again often a dot or shape) at a matching
158 (valid) or different (invalid) peripheral location. When the interval between cue and target is
159 brief (<300ms) (Klein, 2000; Posner & Cohen, 1984), participants typically respond with faster
160 reaction times to valid as opposed to invalid targets, demonstrating attentional capture by the
161 cue. Such designs have typically been used to measure attention capture within the visual field
162 without eye movement (covert attention) (Posner & Cohen, 1984), but have also been used in
163 conjunction with eye-tracking technology to demonstrate the effectiveness of peripheral cues
164 in capturing overt attention in situations where participants are instructed to look toward the
165 oncoming target or have the freedom to do so as part of making a manual response (Caldani et
166 al., 2020; Gobel & Giesbrecht, 2020; MacInnes & Bhatnagar, 2018). Eye-movement latencies
167 toward targets are typically faster when targets were preceded by valid as opposed to invalid
168 cues meaning the targets are foveated more quickly and potentially for longer.

169 Recently, Ogden et al., (2020) used eye-tracking to examine the role of overt attention
170 allocation in emotional distortions to time. Participants estimated the duration of high arousal
171 negative, high arousal positive and neutral IAPS images which appeared on the left or right
172 side of visual space. Participants were instructed they could ignore peripheral cues that
173 preceded each target image, but were free to move their eyes. Two measures of overt attention
174 were taken; time to first fixation (TOFF) and dwell time. TOFF was a measure of the time it
175 took a participant to first fixate on the to-be-timed stimulus and was therefore a measure of
176 attention orientation. Dwell time was the total amount of time that a participant spent fixated
177 on the to-be-timed stimulus and was therefore a measure of sustained attention. TOFF was
178 therefore theorized to reflect switch closure latency and dwell time was thought to reflect
179 sustained attention to time i.e. the closure of the gate. Despite obtaining effects of emotional
180 valence on time estimates and TOFF there was no significant relationship between measures
181 of overt attention allocation and emotional distortions to time. This raises the possibility that
182 the role of overt attention allocation in time perception is perhaps small. This suggestion is
183 supported by Enns et al's., (1999) belief that the lengthening of perceived duration by

184 endogenous valid spatial cues could not only be explained by faster stimulus onset detection.
185 Further research testing the relationship between eye-movement measures of overt attention
186 allocation and temporal estimates is therefore required to establish how, if at all, overt attention
187 affects time perception.

188 *The current study*

189 The current study sought to further develop our understanding of the precise nature of
190 the attentional processes employed during timing. Specifically, the study sought to aid
191 understanding of whether the switch and gate described in SET and the AGM are a form of
192 overt attentional processing. This was achieved by establishing whether overt attention
193 allocation was related to the perceived duration of an event. Overt attention allocation was
194 therefore quantified by recording eye-movements during a modified spatial cueing task,
195 recording the onset and duration of foveations of to-be-timed targets. The study also aimed to
196 establish whether the two predictions of SET and the AGM were accomplished through overt
197 attentional allocation. The first test was whether sustained overt attention to a to-be-timed
198 stimulus was predictive of its perceived duration. This constitutes a test of whether the
199 proposed role of the attentional gate in timing is accomplished through the maintenance of
200 overt attention on the to-be-timed stimulus. The second was to test whether differences in overt
201 attention orientation latency for valid and invalidly cued stimuli were predictive of differences
202 their perceived duration. This constitutes a test of whether the proposed operation of the switch
203 in SET and the AGM is accomplished through shifts in overt attention.

204 Participants completed a modified spatial cueing task in which, following the
205 presentation of a fixation cross, a cue in the form of a black rectangle was presented in the left
206 or right half of the screen. Following cue offset a target stimulus was presented in the form of
207 a black square. The target appeared in either the same location as the cue (valid cue) or on the
208 opposite side of the screen (invalid cue). Participants were required to estimate, in milliseconds,
209 the duration of the target following target offset. Two key target durations were studied; short
210 (1400ms) and long (2100ms). Their repeated presentation was disguised by the presentation of
211 target stimuli with the duration of which was selected at random. Eye-movements were
212 recorded throughout the task. Two measures of eye-movement were taken on each trial; time-
213 of-first fixation (TOFF) and dwell time. TOFF was defined as the duration in milliseconds from
214 target onset to the first fixation on the target and is therefore a measure of latency in overt
215 attentional orientation toward the to-be-timed stimulus. Dwell time was defined as the total

216 duration in milliseconds of fixations that participants made to the to-be-timed-stimulus during
217 its presentation and is therefore a measure of sustained overt attention to the to-be-timed-event
218 throughout its time on screen. The difference in mean estimates, estimate variability, TOFF
219 and dwell time between validly cued and invalidly cued trials was calculated for the short and
220 long target durations separately. The relationships between these values were then tested for
221 the short and long target durations separately.

222 Both SET and the AGM suggest that more rapid orientation of spatial attention to the
223 location of the to-be-timed event will lengthen its perceived duration. Consistent with previous
224 cueing studies, it was expected that duration estimates would be longer and less variable for
225 valid cue trials than invalid cue trials, replicating the findings of Seifried & Ulrich (2011). This
226 would reflect enhanced attentional processing of the to-be-timed target in the valid than
227 invalidly cued conditions. In addition, TOFF was expected to be longer on invalidly cued trials
228 than validly cued trials, replicating the findings of previous studies of cued overt attention
229 (Caldani et al., 2020; Gobel & Giesbrecht, 2020 MacInnes & Bhatnagar, 2018). Conversely,
230 dwell times were expected to be longer on validly cued trials than invalidly cued trials, as
231 participants were expected to fixate on validly cued targets earlier than invalidly cued targets
232 and no rival stimulus would recapture attention.

233 If the operation of the attentional gate (AGM) is determined by the amount of overt
234 attention paid to time *throughout* the to-be-timed event, it would be expected that dwell times
235 would be positively correlated with duration estimates and negatively correlated with estimate
236 variability. Therefore, longer dwell times would be expected to be associated with longer less
237 variable duration estimates. However, if the gate primarily functions on the basis of covert
238 attentional processing we may expect little or no relationship between measures of dwell time
239 and duration estimates and estimate variability. Furthermore, if the operation of the switch is
240 governed by shifts in overt attention, it would be expected that differences in TOFF and dwell
241 time between the valid and invalidly cued trials would be predictive of differences in duration
242 estimates and estimate variability between the valid and invalidly cued trials. Therefore, longer
243 TOFFs would be expected to be associated with shorter duration estimates, and shorter dwell
244 times would be expected to be associated with shorter duration estimates. However, if switch
245 opening and closure latency is governed by covert attentional processing systems we may
246 expect little or no relationship between measures of dwell time and duration estimates and
247 estimate variability.

248 Method

249 *Participants*

250 Fifty participants were recruited via email volunteer sampling from Liverpool John
251 Moores University and the general population. Participants were given a £5 shopping voucher
252 in exchange for participation. Participants were aged 18 to 35 years old (M=20.68 years,
253 SD=3.37 years) with 37 females and 13 males participating. All participants were required to
254 have normal or corrected to normal vision. The study was approved by Liverpool John Moores
255 University Research Ethics Committee and all participants gave informed written consent. The
256 study was conducted in accordance with the principles expressed in the Declaration of Helsinki.

257 *Apparatus*

258 *Eye movement recording:* Eye-tracking was carried out using a Tobii Pro X3-120 monitor
259 mounted eye-tracker, sampling at 120Hz. Participants sat approximately 500mm away from
260 the monitor. Prior to beginning the task each participant underwent a five-point calibration
261 procedure and the experimenter repeated the calibration if they judged it to be unacceptable.
262 Calibration was repeated at the half-way point during the task. Participants completed three
263 practise trials to orient them to the demands and timing of the task. All stimuli were presented
264 against a white background on a monitor with an actual screen size of 474mm (width) by
265 296mm (height). Stimuli were displayed on Hanns.G Hi221 22" monitor with a resolution of
266 1680 by 1050 pixels and a 60Hz refresh rate.

267 *Procedure*

268 The basic experimental procedure was as follows. Participants completed an initial five-
269 point calibration exercise. They then completed three practice trials of the modified verbal
270 estimation task followed by a further 63 trials of a modified verbal estimation task in which
271 they had to judge how long a target was presented on the screen for following either a valid or
272 invalid cue. Participants then re-completed the recalibration exercise followed by a further 63
273 trials of the modified verbal estimation task. The total experiment lasted for approximately 30
274 minutes.

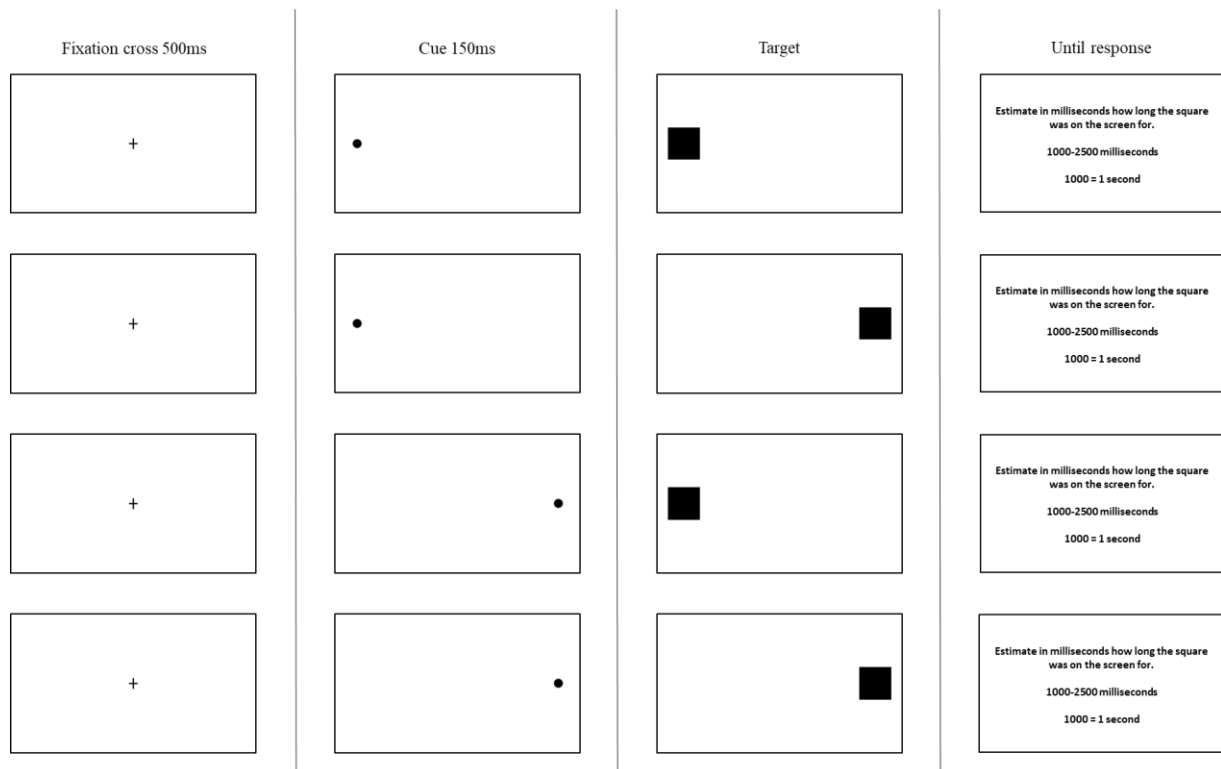
275 *Eye-movements calibration:* Participants completed a five-point calibration procedure that
276 required them to make saccades to five locations (the centre and four corners of the screen)
277 dictated by a moving white dot. When the dot stopped moving on reaching each of the five
278 locations the participants were instructed to fixate on it until it moved again. Calibration

279 accuracy, represented by error bars in each location, was visually inspected and the procedure
280 repeated if considered necessary.

281 *Verbal estimation task:* A modified version of verbal estimation was developed for this task.
282 Participants were informed that, on each trial, they would see a fixation cross, a cue and a target
283 stimulus and that their task was to estimate, in milliseconds, how long the target stimulus was
284 presented on the screen for. Participants were informed that the target was always presented
285 for between 1000ms and 2500ms. In order to ensure that participants' eye-movements were
286 naturalistic and comparable to those in a typical verbal estimation task, participants were given
287 no specific instructions regarding eye-movements except that they were requested to look
288 toward this fixation cross at the start of each trial.

289 At the start of each trial a black fixation cross (1.27° by 1.27°) was presented in the
290 centre of the screen on a white background for 500ms. This was followed by a cue, in the form
291 of a black oval (1.09° by 1.71° , and presented 17.45° horizontally from centre and $.19^\circ$ below
292 centre) which was presented for 150ms. On 50% of trials the cue was presented to the left-hand
293 side of the screen and on 50% of trials it was presented to the right hand side. Following cue
294 offset, the target stimulus was presented in the form of a black rectangle (60mm by 40mm,
295 0.67° by 0.46°) which was presented so that its centre was 80mm from the side of the screen
296 (left or right depending on trial validity) and 150mm from the top of the screen on a white
297 background. The duration of target presentation was determined by the trial type. There were
298 three types of target presentation duration 1) short targets, presented for 1400ms, 2) long
299 targets, presented for 2100 ms and 2) random targets, presented for a duration, selected at
300 random, from a range of 1000ms - 2500ms. Random targets were included to disguise the
301 repeated use of short and long targets. Data from random targets was not analysed (e.g.
302 Piovesan, Mirams, Poole, Moore & Ogden, 2019). Following target presentation participants
303 were instructed to verbalise their estimate and it was recorded by the experimenter. No
304 performance feedback was given. See Figure 2 for trial diagram.

305 Figure 2: Trial structure schemata showing valid and invalid trials for left and right target
306 locations.



307

308 There were two trial types, valid and invalid. On valid trials, the cue and the target
 309 stimulus occurred in the same spatial location. On invalid trials however, the cue and the target
 310 appeared in different spatial locations (see Figure 1 for illustration). 58% of trials were valid
 311 and 42% of trials were invalid. On 50% of valid and invalid trials the target was presented on
 312 the left side of the screen, on the remaining 50% of trials the target was presented on the right
 313 side of the screen. Across the whole experiment there were a total of three practice trials, 48
 314 short trials (of which 50% were valid) and 48 long trials (of which 50% were valid). There
 315 were a further 38 random trials of which 30 were valid). All trials were presented in a random
 316 order.

317 *Data analysis:*

318 *Eye movement:* Measures of dwell time and TOFF were generated within Tobii Pro Studio
 319 (version 3.4.8.1348) through the creation of areas of interest. These were centred on the target
 320 stimuli and made 10 pixels larger on either side of the stimulus rectangle to account for small
 321 errors in eye position tracking resulting in regions of . Mean, minimum and maximum dwell
 322 times and TOFF, and their standard deviations were calculated at the participant level within
 323 Tobii Studio and these statistics were first visually inspected for outliers / artefacts.

324 *Verbal estimation:* time estimates for the short and long targets were each assessed using two
 325 measures: 1) mean estimate, 2) coefficient of variation (CoV). Mean verbal estimate was

326 calculated as the average estimate given for the short and long target. CoV was calculated using
327 the following formula for the short and long target separately for each participant; standard
328 deviation/mean estimate. A CoV of zero indicates no variability.

329 In accordance with Steinborn, Langer, Flehmig & Huestegge (2018), an initial split half
330 reliability analysis was performed on measures of TOFF, dwell time and duration estimates.
331 Significant positive correlations were observed between measures taken from the first half the
332 study (trials 1-63) and the second half of the study (trials 64-126) for TOFF ($r = .39, p = .006$),
333 dwell time ($r = .62, p < .001$), duration estimates ($r = .79, p < .001$) and CoV ($r = .69, p < .001$)
334 suggesting good reliability between measures taken in the first and second half of the task.

335 Results

336 Data from one participant was removed from the dataset because an equipment failure meant
337 that eye-movements were not recorded. The following analysis is therefore based on the
338 remaining 49 participants.

339 Table 1: Descriptive statistics for the measures of temporal perception and eye-movements.

| Trial Type | Mean estimate ms (SD) | Estimate skew | Estimate kurtosis | Mean CoV (SD) | CoV skew | CoV kurtosis | Mean TOFF ms (SD) | TOFF skew | TOFF kurtosis | Mean dwell time ms (SD) | Dwell time skew | Dwell time kurtosis |
|------------------|-----------------------------|------------------|----------------------|---------------------|-------------|-----------------|-------------------------|--------------|------------------|-------------------------------|-----------------------|---------------------------|
| Valid Short | 1516.97 (222.05) | 0.17 | -0.58 | 0.18 (0.06) | -0.29 | -0.19 | 198.20 (242.05) | 1.98 | 4.03 | 1212.90 (194.43) | -1.58 | 2.66 |
| Invalid Short | 1449.36 (219.93) | 0.53 | -0.05 | 0.20 (0.07) | -0.40 | 0.29 | 401.60 (247.38) | 3.00 | 10.96 | 1033.40 (166.59) | -1.73 | 2.67 |
| Valid Long | 2002.34 (171.99) | 0.29 | 0.60 | 0.15 (0.06) | 0.86 | 0.86 | 195.70 (209.84) | 1.48 | 1.86 | 1760.70 (364.85) | -1.85 | 3.84 |
| Invalid Long | 1975.58 (173.05) | 0.08 | 0.02 | 0.16 (0.06) | 0.46 | -0.16 | 410.20 (338.77) | 3.17 | 11.79 | 1590.00 (329.92) | -1.29 | 0.66 |

340

341

342

343 *Eye-movements:*

344 *Attention orientation latency:* Table 1 shows mean TOFF and dwell times for the short and
345 long target durations preceded by valid and invalid cues. Examination of Table 1 suggests that
346 the latency of TOFF was greater for the invalid than valid cues, which supports the
347 effectiveness of the cueing task in influencing the speed at which participants were able to
348 fixate on the targets. Table 2 shows the results of a repeated measures ANOVA with within
349 subjects factors of cue (valid vs invalid), location (left side cue vs right side cue) and target
350 duration (short vs long). Examination of Table 2 confirms a significant effect of cue validity
351 on TOFF, suggesting that cue validity affected overt attention orientation.

352 *Sustained attention:* Examination of the dwell times in Table 1 suggests that dwell times were
353 longer for validly cued trials and for long target trials than for invalidly cued trials and short
354 target trials, again supporting the efficacy of the cueing task in influencing the amount of time
355 that participants were able to spend gazing at the targets. The analysis of dwell times presented
356 in Table 2 shows significant effects of cue validity and target duration on dwell times. Post-
357 hoc testing of the interaction between cue validity and cue location suggested that the
358 difference in dwell times between valid and invalid trials was greater for trials with a right cue
359 location than a left cue location ($p < .01$). These findings confirm that cue validity and target
360 duration affected the length of sustained attention to the to-be-timed stimulus.

361

362 *Time estimates*

363 *Mean estimates:* Examination of the mean estimates in Table 1 suggests that longer estimates
364 were given for validly cued trials and trials with a long target duration. The mean estimate
365 analysis presented in Table 2 shows significant main effect of cue validity and target duration.
366 Post-hoc analysis of the significant two-way interaction between cue validity and target
367 duration confirmed that cue validity had a greater effect on estimates for the short target than
368 for the long target ($p < .05$). Furthermore post-hoc analysis of the interaction between cue
369 validity and cue location confirmed that there was no difference in estimates for invalid trials
370 however for valid trials estimates were longer for right cue locations ($p < .001$). Together these
371 finding confirm that participants were sensitive to duration, giving longer estimates for longer
372 target durations. They also confirm that cue validity effectively affected time estimates.

373

374 *Coefficient of variation:* Examination of the CoVs in Table 1 suggest that variability was
375 greater for the invalid than valid trials. Variability was also greater for the shorter than longer
376 target durations. Examination of the analysis in Table 2 confirmed a significant effects of cue
377 validity and target duration on CoV suggesting more variable estimates for longer durations.
378

379 Table 2: Results of the effects of cue validity (valid vs invalid), target duration (short vs long)
 380 and cue location (left vs right) on attention orientation latency, sustained attention, mean
 381 estimates and CoV.

| Variable | Source | <i>df</i> | <i>F</i> | <i>p</i> | η_p^2 |
|------------------------|--|-----------|----------|----------|------------|
| Orientation latency | Cue validity | 1, 48 | 31.45 | <.001 | .400 |
| | Target duration | 1, 48 | .30 | .63 | .005 |
| | Cue location | 1, 48 | .14 | .71 | .003 |
| | Cue validity * Target duration | 1, 48 | .03 | .85 | .001 |
| | Cue validity * Cue location | 1, 48 | .06 | .81 | .001 |
| | Target duration * Cue location | 1, 48 | .40 | .53 | .008 |
| | Cue validity * Cue location * Target duration | 1, 48 | .56 | .46 | .010 |
| Sustained attention | Cue validity | 1, 48 | 149.33 | <.001 | .76 |
| | Target duration | 1, 48 | 411.77 | <.001 | .90 |
| | Cue location | 1, 48 | .85 | .36 | .02 |
| | Cue validity * Target duration | 1, 48 | .11 | .74 | .002 |
| | Cue validity * Cue location | 1, 48 | 4.42 | .04 | .08 |
| | Target duration * Cue location | 1, 48 | 3.51 | .07 | .06 |
| | Cue validity * Cue location * Target duration | 1, 48 | .13 | .73 | .003 |
| Mean estimates | Cue validity | 1, 48 | 18.33 | <.001 | .28 |
| | Target duration | 1, 48 | 523.67 | <.001 | .92 |
| | Cue location | 1, 48 | 2.14 | .15 | .04 |
| | Cue validity * Target duration | 1, 48 | 4.98 | .03 | .09 |
| | Cue validity * Cue location | 1, 48 | 4.85 | .03 | .09 |
| | Target duration * Cue location | 1, 48 | 2.85 | .10 | .06 |
| | Cue validity * Cue location * Target duration | 1, 48 | .68 | .41 | .01 |
| CoV | Cue validity | 1, 48 | 7.09 | .01 | .13 |
| | Target duration | 1, 48 | 24.20 | <.001 | .33 |
| | Cue location | 1, 48 | .26 | .62 | .005 |
| | Cue validity * Target duration | 1, 48 | .48 | .49 | .01 |
| | Cue validity * Cue location | 1, 48 | 1.30 | .20 | .03 |
| | Target duration * Cue location | 1, 48 | .78 | .38 | .02 |

| | | | | |
|---|-------|-----|-----|------|
| Cue validity * Cue location * Target duration | 1, 48 | .40 | .53 | .008 |
|---|-------|-----|-----|------|

382

383 *The relationship between eye-movements and perceived duration*

384 To establish whether there was a relationship between overt looking time and perceived
 385 duration, Pearson’s correlations were used to assess the relationship between dwell time and
 386 duration estimates and estimate variability for the short and long, valid and invalid conditions
 387 separately (see Table 3).

388

389 Table 3: Inter-correlation coefficients between eye-movement variables and measures of time
 390 estimation. Panel a shows data from the short valid trials, panel b shows data from the short
 391 invalid trials, panel c shows data from the long valid trials and panel d shows data from the
 392 long invalid trials. Coefficients marked with a * are significant at $p < .05$, correlations in bold
 393 test the relationship between measures of time and measures of eye-movement.

394 a) Short Valid

c) Long Valid

| | CoV | TOFF | Dwell time |
|------------|--------|-------------|------------|
| Estimate | -.38** | -.16 | .03 |
| CoV | - | .13 | .10 |
| TOFF | - | - | -.57** |
| Dwell time | - | - | - |

| | CoV | TOFF | Dwell time |
|------------|--------|--------------|---------------|
| Estimate | -.63** | -.11 | .22 |
| CoV | - | -.001 | -.44** |
| TOFF | - | - | -.55** |
| Dwell time | - | - | - |

395

396 b) Short Invalid

d) Long Invalid

| | CoV | TOFF | Dwell time |
|------------|--------|-------------|-------------|
| Estimate | -.31** | -.02 | .15 |
| CoV | - | -.04 | -.21 |
| TOFF | - | - | -.58** |
| Dwell time | - | - | - |

| | CoV | TOFF | Dwell time |
|------------|--------|-------------|--------------|
| Estimate | -.67** | .16 | .19 |
| CoV | - | -.19 | -.31* |
| TOFF | - | - | -.18 |
| Dwell time | - | - | - |

397

398 Examination of Table 3 suggests that for short target durations, eye-movements did not
 399 correlate with measures of duration perception (mean estimates and CoV). For long target
 400 durations, eye-movements did not correlate with mean estimates of duration, however there

401 were significant negative correlations between dwell time and CoV for both valid and invalid
 402 trials. However, the skew of some measures may have affected these findings.

403 Multiple simple linear regression analysis demonstrated that for long target durations
 404 with valid cues, eye-movement variables explained 23.00% of the variance in COV ($R^2 = 26.30$,
 405 $F(2, 48) = 8.21$, $p = .001$). TOFF ($\beta = -.30$, $p = .05$) and dwell time ($\beta = -.59$, $p = .001$) were
 406 both significant predictors. For long trials with invalid cues, eye-movement variables explained
 407 12.60% of the variance in COV ($R^2 = 16.20$, $F(2, 48) = 4.46$, $p = .02$). Dwell time was a
 408 significant predictor ($\beta = -.36$, $p = .02$) but TOFF was not ($\beta = -.26$, $p = .07$). No significant
 409 model fits could be found for short valid estimates $F(2, 48) = .76$, $p = .47$ or COV $F(2, 48) =$
 410 $.41$, $p = .67$, short invalid estimates $F(2, 48) = .71$, $p = .50$ or COV $F(2, 48) = 2.06$, $p = .14$,
 411 long valid estimates $F(2, 48) = 1.21$, $p = .31$ or long invalid estimates $F(2, 48) = 1.85$, $p = .17$.
 412 This suggest that sustained attention is related to the variability of long estimates of duration,
 413 rather than the estimate value itself, with lower levels of sustained attention being associated
 414 with increased estimate variability for long target durations.

415
 416 To establish whether the effect of cue validity on mean estimates and estimate
 417 variability was related to the effect of cue validity on attention orientation and selective
 418 attention, the difference in TOFF, dwell time, mean estimates and COV for validly and
 419 invalidly cued trials was calculated separately for the short and long target durations. The
 420 relationship between these measures was then assessed using Pearson's correlation and p-
 421 values were adjusted for multiple comparisons (see Table 4).

422
 423 Table 4: Correlation coefficients between measures of eye-movement variables and measures
 424 of time estimation. Coefficients marked with a * are significant at $p < .05$.

| | | TOFF Short | Dwell Time Short |
|-------|----------|------------|------------------|
| Short | Estimate | -.37* | .34* |
| | Cov | .24 | -.25 |
| | | TOFF Long | Dwell Time Long |
| Long | Estimate | -.33 | .09 |
| | CoV | .03 | .11 |

433 Multiple regression was used to test whether differences in TOFF and dwell time between the
434 valid and invalidly cued trials predicted differences in mean estimates and CoV between the
435 valid and invalidly cued conditions. For short target durations, eye-movement changes
436 explained 15.90% of the variance in the difference between estimates for the valid and invalidly
437 cued conditions ($R^2 = 19.40$, $F(2, 48) = 5.55$, $p = .007$). TOFF was a significant predictor ($\beta =$
438 $-.30$, $p = .04$) but dwell time was not ($\beta = .25$, $p = .08$). No significant model fit could be found
439 for the change in CoV between the valid and invalid conditions for the short target duration
440 $F(2, 48) = 2.33$, $p = .11$. For the long target duration conditions, no significant model fits were
441 found for mean estimates $F(2, 48) = 2.90$, $p = .07$ or CoV $F(2, 48) = .32$, $p = .73$.

442 *Discussion*

443 This study examined the relationship between overt attention allocation and the
444 perceived duration of valid and invalidly cued targets, using a modified verbal estimation task.
445 Overt attention allocation was quantified using two measures of eye-movements; TOFF which
446 measured the latency of overt attentional orientation to the to-be-timed stimulus, and dwell
447 time, which measured sustained overt attention to the to-be-timed stimulus throughout its
448 presentation. Of key interest was whether there was a relationship between sustained overt
449 attention and perceived duration, and whether the effect of cue validity on measures of attention
450 orientation and sustained attention were predictive of the effect of cue validity on mean
451 duration estimates and the variability of duration estimates.

452

453 The results show that the spatial cueing manipulation successfully modulated duration
454 estimates. Duration estimates were shorter when the to-be-timed target was preceded by an
455 invalid spatial cue than a valid spatial cue. Estimates were also more variable for invalidly cued
456 targets than validly cued targets. This confirms the findings of Seifried & Ulrich (2011) and
457 Yershurun and Marom (2008) that exogenous spatial cues can modify the perceived duration
458 of subsequent events, resulting in shorter duration estimates for invalidly cued targets than for
459 validly cued targets. Our findings expand on these studies by demonstrating the effects with
460 shifts of overt rather than covert attention. In addition, the use of a verbal estimation method
461 in the current study, as opposed to the duration categorisation tasks or equality judgement tasks
462 used in the previous research demonstrates that exogenous cueing effects are robust across
463 experimental paradigms. Furthermore, the use of a supra-second duration range, as opposed to
464 the sub-second ranges used in Seifried & Ulrich (2011) and Yeshurun and Marom (2008)
465 confirms that exogenous spatial cues can affect the perceived duration of longer stimuli.

466

467 The eye-movement recordings confirmed that the spatial cueing manipulation was
468 effective in modifying overt attention allocation. TOFF was significantly longer in the invalid
469 cue condition than the valid cue condition, suggesting faster orientation of overt attention to
470 the target on validly cued than invalidly cued trials. This replicates the findings of Caldani et
471 al., (2020), Gobel and Giesbrecht (2020) and MacInnes and Bhatnagar (2018) who also
472 reported faster eye-movement orientations to validly cued targets than invalidly cued targets.
473 There was no effect of target duration on TOFF, suggesting that the effects of cue validity were
474 comparable for the longer and shorter target durations. Dwell times were significantly longer
475 for the longer target than the shorter target, confirming that overt attention was sustained on
476 the longer target for a greater amount of time than for the shorter target. Dwell times were also
477 significantly longer in the valid condition than the invalid condition. These findings suggest
478 that the modification of the cueing task to include duration estimation did not alter the effect
479 of cue validity on overt selective attention orientation.

480

481 Analysis of the relationship between measures of eye-movements and perceived
482 duration revealed some expected and unexpected relationships. To test whether the period with
483 which overt attention is sustained on the to-be-timed stimulus is related to its perceived
484 duration, correlation and regression analysis was performed on the mean estimates, COV, dwell
485 time and TOFF from each condition. Analysis of the relationship between sustained attention,
486 indexed by dwell time, and mean estimates suggested that how long overt attention is sustained
487 on a stimulus is not significantly related to its perceived duration.

488

489 The AGM suggests that changes in sustained attention to time throughout the to-be-
490 timed stimulus affect the stimulus' perceived duration and the variability of that representation.
491 However, it does not specify whether this attention needs to be overt or covertly focused on
492 the to-be-timed event. In the current study, no relationships were observed between measures
493 of overt sustained attention and perceived stimulus length, however, overt sustained attention
494 was significantly related to the variability of duration estimates, but only for the longer target
495 duration, not the shorter one. Reductions in overt sustained attention therefore only appear
496 affect the variability of the perceived duration of longer stimuli.

497

498 Taken together, the relationships between sustained overt attention and perceived
499 duration appear minimal, perhaps suggesting that changes in overt sustained attention to a

500 timed stimulus do not influence its perceived duration. However, this does not mean that
501 sustained attention is not required for temporal processing. Instead, the absence of an effect of
502 overt attention perhaps indicates that sustained attention to a to-be-timed-event is achieved
503 primarily through covert attention processes, particularly for shorter duration ranges. For
504 example, the presence of a to-be-timed event may be monitored in peripheral vision, without
505 the need for the stimulus to be foveated, using covert attentional processing. Here, fluctuations
506 in covert attention would govern the opening and closing of the attentional gate results in
507 alterations in perceived duration. We therefore tentatively suggest that these findings indicate
508 that time is primarily monitored using covert attentional processes.

509

510 The observation that decreases in overt sustained attention were associated with more
511 variable duration representations does however suggest that for longer stimulus durations, overt
512 attentional systems may be recruited to monitor duration. This raises the possibility that as
513 stimulus presentation duration increases there is a shift from covert monitoring toward using
514 more overt attentional monitoring and that fluctuations in this overt monitoring affect the
515 variability of the duration estimate. Overt attention may only be recruited during longer
516 duration presentations because shorter intervals places less demand on sustained attention than
517 the processing of longer ones (Lewis & Miall, 2003 a and b), reducing the need for overt
518 monitoring during short presentations. Accordingly, fluctuations in overt attention may
519 therefore be more prevalent during the processing of longer intervals than shorter ones,
520 providing greater capacity for these fluctuations to influence estimate variability. However, if
521 overt sustained attention resources are used to a greater extent in the monitoring of longer
522 durations, it is unclear why fluctuations in overt sustained attention would not also affect the
523 perceived length of a stimulus rather than just its variability. This is because, according to the
524 AGM, fluctuations in sustained attention affect the length and variability of an estimate by
525 reducing the overall level of accumulation. Future research should therefore further explore the
526 parameters under which covert and overt sustained allocation of attention influence the
527 processing of short and long durations.

528

529 To test whether the predictions of SET and the AGM regarding switch operation, were
530 accomplished through overt attention allocation, the relationship between the difference in
531 mean estimates, estimate COV and TOFF between the valid and invalid conditions was
532 calculated. This analysis revealed that for the short target duration, the difference in mean
533 estimates for the valid and invalid cue conditions was predicted by the difference in TOFF

534 between the valid and invalid cue conditions. For the long target duration, changes in TOFF
535 between valid and invalid trials were not predictive of changes in estimate. Differences in
536 TOFF were not predictive of differences in COV suggesting that overt attention orientation
537 latency does influence the variability of duration estimates. These findings therefore suggest
538 that whilst the relative differences in overt attention orientation latency can explain relative
539 differences in perceived duration of short stimuli, they cannot explain relative differences in
540 the perceived duration of longer stimuli. Furthermore, changes in overt attention orientation
541 latency are only predictive of *relative differences* in estimates between different conditions.
542 The latency with which an individual stimulus is orientated to is not in itself predictive of its
543 perceived duration.

544

545 According to SET and the AGM, the switch closes when the to-be-timed stimulus is
546 identified/attended to. Increases in the latency of this closure may therefore reduce perceived
547 duration. However, neither model specifies whether switch operations is governed by overt or
548 covert attention orientation. The findings of the current study suggest that the switch may be
549 governed by overt attention processing, because for shorter durations at least, longer overt
550 latencies are associated with shorter duration estimates. For longer durations, it is still possible
551 that the stimuli were initially orientated to using overt attention, however it is possible that the
552 relatively small effect of orientation latency is wiped out by increases in timing variability
553 introduced by sustaining attention (covertly or overtly) over a longer period of time. However,
554 it should be noted that overt attention orientation typically follows covert attention orientation
555 (Posner, 1980). It is therefore possible that the switch may be primarily closed (and opened)
556 by switches in covert attention and that the effects observed in this study represent secondary
557 influences of overt allocation following covert attention allocation.

558

559 Collectively, the findings of this study suggest that overt attention allocation has small
560 limited effects on duration estimates. This, coupled with Ogden et al's (2021) findings of
561 limited relationships between measures of overt attention and emotional distortions to time
562 suggests that covert attentional processes may be primarily responsible for governing the
563 operation the switch and the attentional gate. To-be-timed events do not therefore necessarily
564 need to be overtly attended to or foveated to be processed, instead it would appear that their
565 duration can be monitored covertly in the periphery. It should be noted however, that the use
566 of a narrow duration range in this paper and Ogden et al., (2020) does not exclude significant
567 effects of overt attention allocation on other duration ranges. For example, it is possible that

568 orientation latency effects would be greater for shorter sub-second durations because the
569 duration of latency would make up a larger proportion of the overall stimulus duration.
570 Similarly, it is possible that there may be more significant effects of overt sustained attention
571 on the perceived duration of longer stimuli (e.g. 10's of seconds or minutes in duration) because
572 of the increased demands associated with a longer processing period. Further research should
573 therefore systematically examine the effect of overt attention allocation on the timing of sub-
574 second to multi-minute stimulus durations.

575

576 *Limitations*

577 The current study used two measures of eye-movements, dwell time and TOFF, which
578 were both taken from target onset. The study did not however measure anticipatory eye-
579 movements prior to target presentation. Consequently, the current study could not examine
580 whether anticipatory shifts in overt attention toward the spatial location of the target also
581 influence perceived duration. Future research should therefore seek to take broader measures
582 of eye-movements and establish how they may relate to perceived duration.

583

584 Although the spatial cueing manipulation used in the current study was successful in
585 altering eye-movements and perceived duration the near equal weighting of the valid and
586 invalid cues may have reduced the effect of cue validity on eye-movements and perceived
587 duration. It is possible that a greater weighting for valid cues may have increased the effect of
588 the cue on perceived duration and or eye-movement, potentially altering the relationships
589 observed between eye-movements and duration perception. Furthermore, because the duration
590 of the cue was constant in all trials, the start of the target was predictable from the appearance
591 of the cue, regardless of cue validity. Future research should therefore use variable onset
592 durations between the cue and the target to prevent the cue being a constant temporal predictor
593 of target onset and to ensure that participants are attending to the target in addition to the cue.

594

595 A final issue is that of the effect of quantization on the relationships between estimates
596 of duration and eye-movements. Verbal estimates of duration are subject to quantization, that
597 is, the tendency to use some numerical values estimates much more frequently than others (see
598 Ogden, Simmons & Wearden, 2020 and Wearden, 2015 for discussion). For example, people
599 preferentially use round numbers such as 100ms, 500ms and 1000ms and rarely use precise
600 estimates such as 127ms or 538ms. It is feasible that this process of quantization may have
601 reduced the relationships observed between eye-movement and perceived duration because,

602 rather than examining the relationship between some raw representation of time and eye-
603 movements, we were examining the effect of a scaled and quantized representation of duration
604 (see Ogden et al., 2020 for discussion). Future research should therefore explore how eye-
605 movements relate to non-quantized duration representations, for example, those produced in
606 discrimination or categorization tasks such as temporal generalization and bisection.

607

608 *Conclusion*

609 The findings of this study show that measures of overt attention allocation are not consistently
610 predictive of perceived duration. Although the relative difference in the perceived duration of
611 valid and invalidly cued stimuli was predicted by differences in overt attention orientation
612 latency, this was only the case for the short target not the long. Furthermore, and perhaps most
613 surprisingly, there was no consistent significant relationship between measures of overt
614 sustained attention and mean duration estimates. Overt looking duration does not therefore
615 equal subjective perceived duration. These findings suggest that the mechanisms used to attend
616 to time (e.g. the switch and the gate) are unlikely to be primarily governed by overt attentional
617 processing systems. Instead, it seems likely that time is attended to using covert attentional
618 processing systems.

619

620

621

622 References

- 623 Allman, M., & Falter, C. (2015). Abnormal timing and time perception in autism spectrum
624 disorder? A review of the evidence. *Time distortions in mind—temporal processing in*
625 *clinical populations*, 37-56.
- 626 Block, R. A., & Zakay, D. (1996). Models of psychological time revisited. In Helfrich, H. (Ed.),
627 *Time and Mind* (pp. 171–195). Kirkland, WA, USA: Hogrefe & Huber.
- 628 Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration
629 judgments: A meta-analytic review. *Acta psychologica*, 134(3), 330-343.
- 630 Buhusi, C. V., & Meck, W. H. (2009). Relativity theory and time perception: single or multiple
631 clocks? *PLoS ONE*, 4, e6268. doi: 10.1371/journal.pone.0006268
- 632 Caldani, S., Isel, F., Septier, M., Acquaviva, E., Delorme, R., & Bucci, M. P. (2020).
633 Impairment in attention focus during the Posner cognitive task in children with ADHD:
634 an eye tracker study. *Frontiers in Pediatrics*, 8. <https://doi.org/10.3389/fped.2020.00484>
- 635 Chen, Z., & O'Neill, P. (2001). Processing demand modulates the effects of spatial attention
636 on the judged duration of a brief stimulus. *Perception & Psychophysics*, 63, 1229–1238.
- 637 Coull, J. T., Vidal, F., Nazarian, B., & Macar, F. (2004). Functional anatomy of the attentional
638 modulation of time estimation. *Science*, 303, 1506-1508. DOI: 10.1126/science.1091573
- 639 De Haan, B., Morgan, P. S., & Rorden, C. (2008). Covert orienting of attention and overt eye
640 movements activate identical brain regions. *Brain research*, 1204, 102-111.
- 641 Droit-Volet, S. (2003). Alerting attention and time perception in children. *Journal of*
642 *Experimental Child Psychology*, 85(4), 372-384.
- 643 Droit-Volet, S. (2016). Development of time. *Current Opinion in Behavioral Sciences*, 8, 102-
644 109.
- 645 Eckstein, M. K., Guerra-Carrillo, B., Singley, A. T. M., & Bunge, S. A. (2017). Beyond eye
646 gaze: What else can eyetracking reveal about cognition and cognitive development?
647 *Dev. Cogn. Neurosci.*, 25, 69–91. doi: 10.1016/j.dcn.2016.11.001
- 648 Enns, J. T., Brehaut, J. C., & Shore, D. I. (1999). The duration of a brief event in the mind's
649 eye. *J. Gen. Psychol.*, 126, 355–372. doi: 10.1080/00221309909595371
- 650 Falter, C. M., Noreika, V., Wearden, J. H., & Bailey, A. J. (2012). More consistent, yet less
651 sensitive: interval timing in autism spectrum disorders. *Quarterly journal of*
652 *experimental psychology*, 65(11), 2093-2107.
- 653 Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Ann. N. Y. Acad.*
654 *Sci.*, 423, 52–77. doi: 10.1111/j.1749-6632.1984.tb23417.x

655 Gil, S., Chambres, P., Hyvert, C., Fanget, M., & Droit-Volet, S. (2012). Children with autism
656 spectrum disorders have “the working raw material” for time perception. *PLoS*
657 *One*, 7(11), e49116.

658 Gobel, M. S., & Giesbrecht, B. (2020). Social information rapidly prioritizes overt but not
659 covert attention in a joint spatial cueing task. *Acta Psychologica*, 211, 103188.

660 Isaksson, S., Salomäki, S., Tuominen, J., Arstila, V., Falter-Wagner, C. M., & Noreika, V.
661 (2018). Is there a generalized timing impairment in Autism Spectrum Disorders across
662 time scales and paradigms?. *Journal of psychiatric research*, 99, 111-121.

663 Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, 4(4), 138-147.

664 Kulke, L. V., Atkinson, J., & Braddick, O. (2016). Neural differences between covert
665 and overt attention studied using EEG with simultaneous remote eye tracking. *Frontiers*
666 *in human neuroscience*, 10, 592. doi.org/10.3389/fnhum.2016.00592

667 Lewis, P. A., & Miall, R. C. (2003). Brain activation patterns during measurement of sub-and
668 supra-second intervals. *Neuropsychologia*, 41(12), 1583-1592.

669 Lewis, P. A., & Miall, R. C. (2003). Distinct systems for automatic and cognitively controlled
670 time measurement: evidence from neuroimaging. *Current opinion in*
671 *neurobiology*, 13(2), 250-255.

672 Lejeune, H. (1998). Switching or gating? The attentional challenge in cognitive models of
673 psychological time. *Behav. Proc.*, 44, 127–145. doi: 10.1016/S0376-6357(98)00045-X

674 Lejeune, H. (2000). Prospective timing, attention and the switch: A response to ‘Gating or
675 switching? gating is a better model of prospective timing’ by Zakay. *Behav. Proc.*, 52,
676 71–76. doi: 10.1016/S0376-6357(00)00136-4

677 MacInnes, W. J., & Bhatnagar, R. (2018). No supplementary evidence of attention to a spatial
678 cue when saccadic facilitation is absent. *Scientific reports*, 8(1), 1-13.

679 Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to
680 perception, attention, and memory. *Psychol. Bull.*, 142, 865–907.
681 <http://doi.org/10.1037/bul0000045>

682 Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief
683 stimulus. *Percept. Psychophys.*, 60, 1305–1317. doi: 10.3758/BF03207993

684 Noreika, V., Falter, C. M., & Rubia, K. (2013). Timing deficits in attention-
685 deficit/hyperactivity disorder (ADHD): evidence from neurocognitive and neuroimaging
686 studies. *Neuropsychologia*, 51(2), 235-266.

687 Ogden, R. S., Simmons, F. R., & Wearden, J. H. (2020). Verbal estimation of the magnitude
688 of time, number, and length. *Psychological Research*, 1-13.

689 Ogden, R. S., Turner, F., & Pawling, R. (2021). An absence of a relationship between overt
690 attention and emotional distortions to time: an eye-movement study. *Timing and Time*
691 *Perception*.

692 Parkhurst, D., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation
693 of overt visual attention. *Vis. Res.*, 42, 107–123. doi: 10.1016/S0042-6989(01)00250-4

694 Piovesan, A., Mirams, L., Poole, H., Moore, D., & Ogden, R. (2019). The relationship between
695 pain-induced autonomic arousal and perceived duration. *Emotion*, 19, 1148–1161. doi:
696 10.1037/emo0000512

697 Posner, M. I. (1980). Orienting of attention. *Q. J. Exp. Psychol.*, 32, 3–25. doi:
698 10.1080/00335558008248231

699 Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G.
700 Bouwhuis (Eds.) *Attention and Performance X: Control of Language Processes* (pp.
701 531-556). Lawrence Erlbaum

702 Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual
703 search. *Q. J. Exp. Psychol.*, 62, 1457–1506. doi: 10.1080/17470210902816461

704 Seifried, T., & Ulrich, R. (2011). Exogenous visual attention prolongs perceived duration.
705 *Atten. Percept. Psychophys.*, 73, 68–85. doi: 10.3758/s13414-010-0005-6

706 Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-
707 down guidance of attention from working memory. *J. Exp. Psychol. Hum. Percept.*
708 *Perform.*, 31, 248–261. doi: 10.1037/0096-1523.31.2.248

709 Steinborn, M. B., Langner, R., & Huestegge, L. (2017). Mobilizing cognition for speeded
710 action: try-harder instructions promote motivated readiness in the constant-foreperiod
711 paradigm. *Psychological Research*, 81(6), 1135-1151.

712 Steinborn, M. B., Langner, R., Flehmig, H. C., & Huestegge, L. (2018). Methodology of
713 performance scoring in the d2 sustained-attention test: Cumulative-reliability functions
714 and practical guidelines. *Psychological Assessment*, 30(3), 339-357.

715 Van der Stigchel, S., & Theeuwes, J. (2007). The relationship between covert and overt
716 attention in endogenous cuing. *Perception & Psychophysics*, 69(5), 719-731.

717 Theeuwes, J., Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of
718 attentional capture on oculomotor control. *J. Exp. Psychol. Hum. Percept. Perform.*, 25,
719 1595–1608. doi: 10.1037/0096-1523.25.6.1595

720 Vogel, D., Falter-Wagner, C. M., Schoofs, T., Krämer, K., Kupke, C., & Vogeley, K. (2019).
721 Interrupted time experience in autism spectrum disorder: empirical evidence from
722 content analysis. *Journal of Autism and Developmental Disorders*, *49*(1), 22-33.

723 Wang, B., Samara, I., & Theeuwes, J. (2019). Statistical regularities bias overt attention.
724 *Attention, Perception, & Psychophysics*, *81*(6), 1813-1821.

725 Wearden, J. H. (2015). Mission: Impossible? Modelling the verbal estimation of
726 duration. *Timing & Time Perception*, *3*(3-4), 223-245.

727 Wearden, J. (2016). *The psychology of time perception*. Springer.

728 Wearden, J. H., O'Rourke, S. C., Matchwick, C., Min, Z., & Maeers, S. (2010). Task switching
729 and subjective duration. *Q. J. Exp. Psychol.*, *63*, 531–543. doi:
730 10.1080/17470210903024768

731 Yeshurun, Y., & Marom, G. (2008). Transient spatial attention and the perceived duration of
732 brief visual events. *Visual Cognition*, *16*(6), 826-848.

733 Zakay, D. (2000). Gating or switching? Gating is a better model of prospective timing (a
734 response to ‘switching or gating?’ by Lejeune). *Behav. Proc.*, *52*, 63–69. doi:
735 10.1016/S0376-6357(00)00141-8

736 Zakay, D., & Block, R. A. (1995). An attentional-gate model of prospective time estimation.
737 In: M. Richelle, V. De Keyser, G. d’Ydewalle, & A. Vandierendonck (Eds), *Time and*
738 *the dynamic control of behavior* (pp. 167–178). Liège, Belgium: Université de Liège.

739 Zakay, D., & Block, R. A. (1997). Temporal cognition. *Curr. Dir. Psychol. Sci.*, *6*, 12–16. doi:
740 10.1111/1467-8721.ep11512604

741