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

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Abstract

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

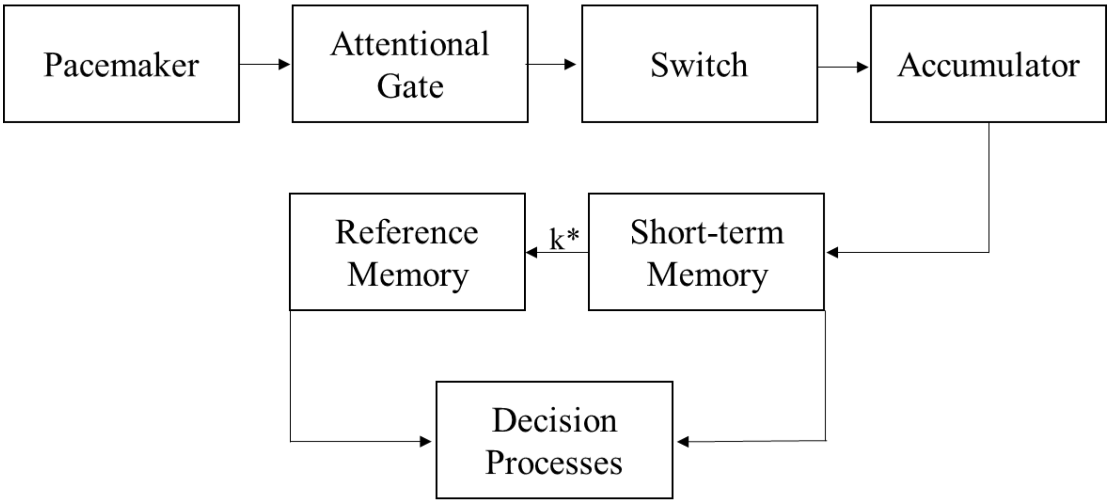
Introduction

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

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

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

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



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

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

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

Although current findings from experimental and individual differences studies support the SET and the AGM's proposed roles of attention in timing there are significant gaps in our understanding of precisely how attention functions during timing. Most importantly perhaps, both SET and the AGM are agnostic about whether timing is accomplished through overt or covert attentional processing systems. Overt attention in the visual domain refers to shifts in attention that involve head or eye movements, whereas covert attention refers to shifts in attentional in the absence of eye or head movement (Posner, 1980). One possibility is that accurate time perception can be achieved solely through covertly attending to the to-be-timed event in the periphery. Here, switch closure and opening would be prompted by shifts in attention which occurred in the absence of eye-movements, or at least in the absence of eye-movements resulting in foveation of the to-be-timed stimulus. Similarly, gate opening and closure would be governed by sustained covert attention on the to-be-timed stimulus in the absence of sustained fixation in the foeva. However, another possibility is that accurate timing is only possible when attention is overtly focused on the to-be-timed event. In this overt attention scenario, for the switch to close and open and for the attentional gate to remain closed, the to-be-timed stimulus would need to be foveated throughout presentation. A further possibility however is that the switch and the gate may be controlled by different attentional processes, for example, covert attention may identify a to-be-timed target, resulting in switch closure. However, this may result in a shift in overt attention to the target resulting in overt control of the attentional gate. The converse is also possible; overt attention may be needed to close the switch, but then covert attention can be used to monitor the to-be-timed event throughout its presentation.

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

One way to integrate objective attention measures of overt attention into timing studies is through the measurement of eye movements. Even though attention and oculomotor systems are traditionally considered as separate modules, even covert attentional shifts appear to involve the oculomotor system to some degree (e.g de Haan et al., 2008; Van der Stigchel & Theeuwes, 2007). Overt attentional shifts at their most basic level can be measured by tracking changes in foveation, which is possible through the use of eye-tracking technology (Kulke et al., 2016; Wang et al., 2019). In typical studies Eye-tracking has been widely used to record changes in endogenous and exogenous overt attention allocation (Parkhurst, Law & Niebur, 2002, Soto, Heinke, Humphreys, & Blanco, 2005, Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999 and see Eckstein, Guerra-Carrillo, Singley, & Bunge, 2017 and Rayner, 2009 for reviews). Simple and elegant spatial cuing tasks, perhaps the best known of which is the Posner paradigm (Posner, 1980), have been used for decades to explore attention capture, including overt exogenous attentional shifts. The Posner paradigm typically involves a participant fixating on a central location after which a cue, often a dot, flash or geometric shape appears at a peripheral location, followed by a target (again often a dot or shape) at a matching (valid) or different (invalid) peripheral location. When the interval between cue and target is brief (<300ms) (Klein, 2000; Posner & Cohen, 1984), participants typically respond with faster reaction times to valid as opposed to invalid targets, demonstrating attentional capture by the cue. Such designs have typically been used to measure attention capture within the visual field without eye movement (covert attention) (Posner & Cohen, 1984), but have also been used in conjunction with eye-tracking technology to demonstrate the effectiveness of peripheral cues in capturing overt attention in situations where participants are instructed to look toward the oncoming target or have the freedom to do so as part of making a manual response (Caldani et al., 2020; Gobel & Giesbrecht, 2020; MacInnes & Bhatnagar, 2018). Eye-movement latencies toward targets are typically faster when targets were preceded by valid as opposed to invalid cues meaning the targets are foveated more quickly and potentially for longer.

Recently, Ogden et al., (2020) used eye-tracking to examine the role of overt attention allocation in emotional distortions to time. Participants estimated the duration of high arousal negative, high arousal positive and neutral IAPS images which appeared on the left or right side of visual space. Participants were instructed they could ignore peripheral cues that preceded each target image, but were free to move their eyes. Two measures of overt attention were taken; time to first fixation (TOFF) and dwell time. TOFF was a measure of the time it took a participant to first fixate on the to-be-timed stimulus and was therefore a measure of attention orientation. Dwell time was the total amount of time that a participant spent fixated on the to-be-timed stimulus and was therefore a measure of sustained attention. TOFF was therefore theorized to reflect switch closure latency and dwell time was thought to reflect sustained attention to time i.e. the closure of the gate. Despite obtaining effects of emotional valence on time estimates and TOFF there was no significant relationship between measures of overt attention allocation and emotional distortions to time. This raises the possibility that the role of overt attention allocation in time perception is perhaps small. This suggestion is supported by Enns et al's., (1999) belief that the lengthening of perceived duration by endogenous valid spatial cues could not only be explained by faster stimulus onset detection. Further research testing the relationship between eye-movement measures of overt attention allocation and temporal estimates is therefore required to establish how, if at all, overt attention affects time perception.

The current study

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

Participants completed a modified spatial cueing task in which, following the presentation of a fixation cross, a cue in the form of a black rectangle was presented in the left or right half of the screen. Following cue offset a target stimulus was presented in the form of a black square. The target appeared in either the same location as the cue (valid cue) or on the opposite side of the screen (invalid cue). Participants were required to estimate, in milliseconds, the duration of the target following target offset. Two key target durations were studied; short (1400ms) and long (2100ms). Their repeated presentation was disguised by the presentation of target stimuli with the duration of which was selected at random. Eye-movements were recorded throughout the task. Two measures of eye-movement were taken on each trial; time-of-first fixation (TOFF) and dwell time. TOFF was defined as the duration in milliseconds from target onset to the first fixation on the target and is therefore a measure of latency in overt attentional orientation toward the to-be-timed stimulus. Dwell time was defined as the total duration in milliseconds of fixations that participants made to the to-be-timed-stimulus during its presentation and is therefore a measure of sustained overt attention to the to-be-timed-event throughout its time on screen. The difference in mean estimates, estimate variability, TOFF and dwell time between validly cued and invalidly cued trials was calculated for the short and long target durations separately. The relationships between these values were then tested for the short and long target durations separately.

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

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

Method

Participants

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

Apparatus

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

Procedure

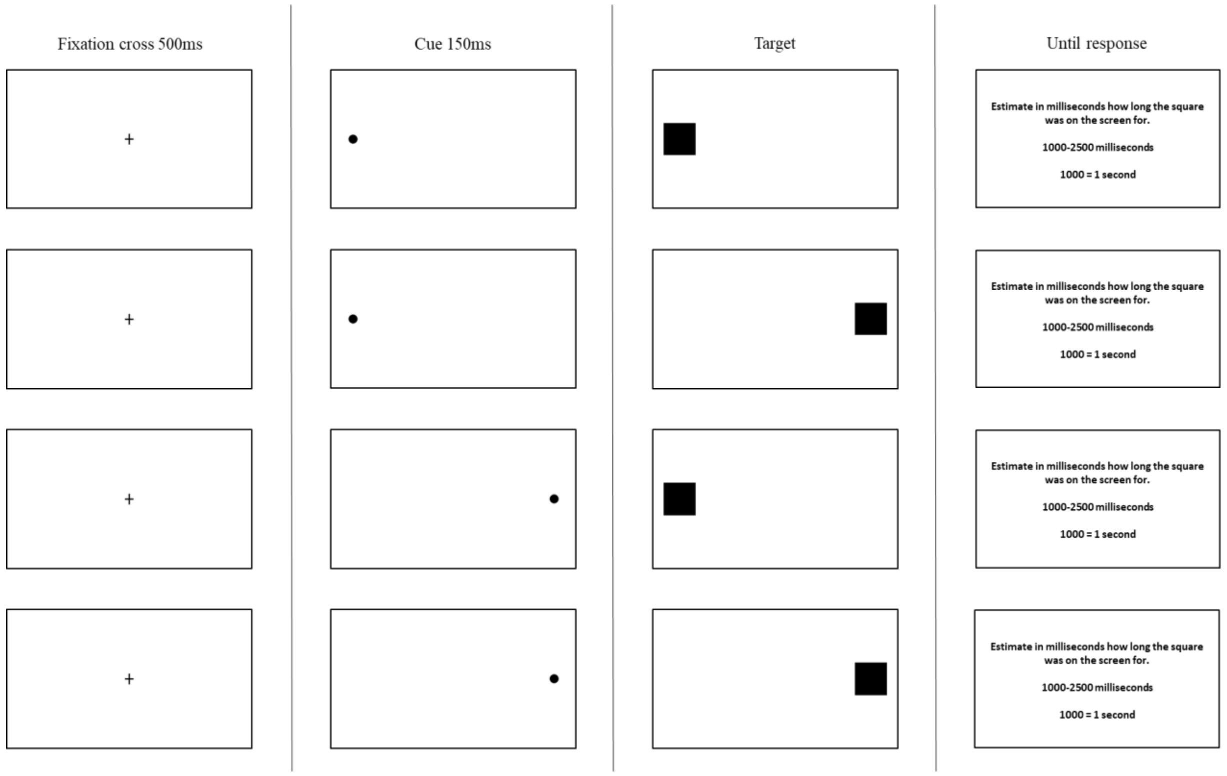
The basic experimental procedure was as follows. Participants completed an initial five-point calibration exercise. They then completed three practice trials of the modified verbal estimation task followed by a further 63 trials of a modified verbal estimation task in which they had to judge how long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

Eye-movements calibration: Participants completed a five-point calibration procedure that required them to make saccades to five locations (the centre and four corners of the screen) dictated by a moving white dot. When the dot stopped moving on reaching each of the five locations the participants were instructed to fixate on it until it moved again. Calibration accuracy, represented by error bars in each location, was visually inspected and the procedure repeated if considered necessary.

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

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

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



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

Data analysis:

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

Verbal estimation: time estimates for the short and long targets were each assessed using two measures: 1) mean estimate, 2) coefficient of variation (CoV). Mean verbal estimate was calculated as the average estimate given for the short and long target. CoV was calculated using the following formula for the short and long target separately for each participant; standard deviation/mean estimate. A CoV of zero indicates no variability.

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

Results

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

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

Eye-movements:

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

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

Time estimates

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

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

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

Variable	Source	*df*	*F*	*p*	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

The relationship between eye-movements and perceived duration

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

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

a) Short Valid

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

c) Long Valid

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

b) Short Invalid

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

d) Long Invalid

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

Examination of Table 3 suggests that for short target durations, eye-movements did not correlate with measures of duration perception (mean estimates and CoV). For long target durations, eye-movements did not correlate with mean estimates of duration, however there were significant negative correlations between dwell time and CoV for both valid and invalid trials. However, the skew of some measures may have affected these findings.

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

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

Table 4: Correlation coefficients between measures of eye-movement variables and measures 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

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

Discussion

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

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

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

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

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

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

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

To test whether the predictions of SET and the AGM regarding switch operation, were accomplished through overt attention allocation, the relationship between the difference in mean estimates, estimate COV and TOFF between the valid and invalid conditions was calculated. This analysis revealed that for the short target duration, the difference in mean estimates for the valid and invalid cue conditions was predicted by the difference in TOFF between the valid and invalid cue conditions. For the long target duration, changes in TOFF between valid and invalid trials were not predictive of changes in estimate. Differences in TOFF were not predictive of differences in COV suggesting that overt attention orientation latency does influence the variability of duration estimates. These findings therefore suggest that whilst the relative differences in overt attention orientation latency can explain relative differences in perceived duration of short stimuli, they cannot explain relative differences in the perceived duration of longer stimuli. Furthermore, changes in overt attention orientation latency are only predictive of *relative differences* in estimates between different conditions. The latency with which an individual stimulus is orientated to is not in itself predictive of its perceived duration.

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

Collectively, the findings of this study suggest that overt attention allocation has small limited effects on duration estimates. This, coupled with Ogden et al's (2021) findings of limited relationships between measures of overt attention and emotional distortions to time suggests that covert attentional processes may be primarily responsible for governing the operation the switch and the attentional gate. To-be-timed events do not therefore necessarily need to be overtly attended to or foveated to be processed, instead it would appear that their duration can be monitored covertly in the periphery. It should be noted however, that the use of a narrow duration range in this paper and Ogden et al., (2020) does not exclude significant effects of overt attention allocation on other duration ranges. For example, it is possible that orientation latency effects would be greater for shorter sub-second durations because the duration of latency would make up a larger proportion of the overall stimulus duration. Similarly, it is possible that there may be more significant effects of overt sustained attention on the perceived duration of longer stimuli (e.g. 10's of seconds or minutes in duration) because of the increased demands associated with a longer processing period. Further research should therefore systematically examine the effect of overt attention allocation on the timing of sub-second to multi-minute stimulus durations.

Limitations

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

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

A final issue is that of the effect of quantization on the relationships between estimates of duration and eye-movements. Verbal estimates of duration are subject to quantization, that is, the tendency to use some numerical values estimates much more frequently than others (see Ogden, Simmons & Wearden, 2020 and Wearden, 2015 for discussion). For example, people preferentially use round numbers such as 100ms, 500ms and 1000ms and rarely use precise estimates such as 127ms or 538ms. It is feasible that this process of quantization may have reduced the relationships observed between eye-movement and perceived duration because, rather than examining the relationship between some raw representation of time and eye-movements, we were examining the effect of a scaled and quantized representation of duration (see Ogden et al., 2020 for discussion). Future research should therefore explore how eye-movements relate to non-quantized duration representations, for example, those produced in discrimination or categorization tasks such as temporal generalization and bisection.

Conclusion

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

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