The time course of attentive tracking

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The temporal characteristics of attentive tracking were studied in three experiments. We measured attentional dwell time and shift time during attentive tracking and showed that when an external cue is available, attention can repeatedly shift between items remarkably quickly. However, because attention is synchronized to this external cue, the time cost of shifting attention is inversely related to tracking rate. Furthermore, we show that during tracking, attentional shifts are likely synchronized to cue onsets rather than offsets. Results are discussed in the framework of a smoothly moving attentional spotlight.

Keywords: visual attention, attentive tracking, attentional spotlight, temporal, time course

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Introduction

The way in which attention shifts around the visual field has been the topic of considerable interest in the last decades. Some researchers advocate a model in which attention can be resolved into discrete attentional episodes (e.g., Remington & Pierce, 1984; Sperling & Weichselgartner, 1995). In such an episodic, or quantal, model, there are many immobile attentional spotlights which can be turned on and off. Shifting attention from one location to another involves turning on a spotlight at the new location and turning off the spotlight at the old location. Conversely, other researchers find support for models in which the attentional spotlight can move smoothly around the visual field (e.g., Shioiri, Cavanagh, Miyamoto, & Yaguchi, 2000; Shioiri, Yamamoto, Kageyama, & Yaguchi, 2002; Shulman, Remington, & McLean, 1979; Tsal, 1983). Generally, these models propose the existence of only one spotlight (Cave & Bichot, 1999), although phenomena such as multiple object tracking have led some to suggest that there might be up to four (Pylyshyn & Storm, 1988).

Given the wide variety of experimental paradigms that have been used to study attentional shifts, it seems plausible that attention uses different mechanisms depending on task demands. For example, several studies have investigated the effects of cueing the focus of attention from one location to another. In such a design, it would be efficient for the visual system to shift attention to the new location discretely, without attending to locations in between. In other experimental conditions, such as attentively tracking a smoothly moving object, smooth movements of attention would be more efficient at keeping attention on the target. Indeed, there is considerable evidence suggesting that attention moves smoothly during attentive tracking, even when attention is tracking an object that itself does not move smoothly, such as an apparent motion stimulus. For example, Shioiri et al. (2000) asked observers to report the perceived location of an element of an apparent motion stimulus and found that the perceived location moved smoothly along the motion path during the interval between stimulus presentations. Their interpretation was that the internal representation of the tracked object continues to move smoothly over time. By assuming that attention moves along with this internal representation, they suggested that attention moves smoothly. In a later set of experiments, Shioiri et al. (2002) probed attention directly and showed that attention does move smoothly over space while tracking.

The majority of experiments studying movements of attention during attentive tracking has focused on the spatial properties of moving attention, demonstrating the presence of attention along a motion path between

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successively attended locations. However, a small number of studies have investigated temporal aspects of attentive tracking. For example, both Verstraten, Cavanagh, and Labianca (2000) and Horowitz, Holcombe, Wolfe, Arsenio, and DiMase (2004) investigated the maximum rate at which attentive tracking was possible. An apparent contradiction between the two studies was recently resolved by Benjamins, Hooge, van der Smagt, and Verstraten (2007), who demonstrated that duty cycle has a strong effect on tracking performance. Benjamins et al. argued that tracking performance is better at lower duty cycles because a disengage signal is available to attention earlier. Clearly, temporal factors play an important role in tracking. In the experiments we report here, we further investigate the temporal implications of the repeated attentional shifts involved in attentive tracking.

Much of the literature studying the time course of shifting attention has used methods that cannot distinguish between moments when attention is moving from item to item and moments when attention has an item selected. Instead, the most commonly reported measure is the temporal sum of these two periods: the total time between attending to successive stimuli. This measure has interchangeably been called both dwell time and shift time, despite encompassing both periods in which attention is dwelling *on* an item and periods in which it is shifting *to* another. In visual search paradigms, for example, the dependent variable is often the slope of the function relating reaction time to the number of items in the display. In other words, the time cost of processing one additional item (Wolfe, 1998). This cost, however, consists of time spent carrying out processing of the item as well as time spent shifting attention. Similarly, the "dwell time" paradigm developed by Duncan, Ward, and Shapiro (1994), which measures the period of time the first of two sequentially presented targets continues to interfere with the second, cannot distinguish whether attention is still engaged on the first target or whether it is shifting to the second target.

In the 3 experiments reported here, observers track an apparent motion stimulus designed to separately measure the time attention is moving from item to item and for how long each item is selected. Therefore, we make a distinction between the quantities dwell time and shift time. We define dwell time as the duration in which attention has selected one of the items. The duration between these periods is defined as shift time, such that dwell time and shift time are mutually exclusive (although in some models of attentional shifts the transition is graded; e.g., Sperling & Weichselgartner, 1995). Since we use a tracking stimulus, the rate at which attention moves (i.e., the number of shifts per unit time or tracking rate) is fixed by the stimulus, and we refer to the period of time between successive cue onsets as the step time. It is important to note that step time is a stimulus property, whereas dwell and shift time are dependent variables calculated from observer responses.

We adapt a stimulus we previously developed to measure when attention arrives at a particular location (Carlson, Hogendoorn, & Verstraten, 2006). Observers view a circular array of running analog clocks that are sequentially cued such that it is possible to track the cued clock with attention. When tracking this stimulus, the experience is as if the hand on the cued clock 'waggles' between two positions, repeatedly sweeping over a small sector of the clock face. The observer's task is to report the earliest (i.e., most counterclockwise) and latest (i.e., most clockwise) edges of this sector. These two positions bracket the period of time during which attention has a clock selected (dwell time) and also allow us to calculate the time spent shifting attention (shift time) (Figure 1).

Experiment 1

In Experiment 1, we investigate how the time course of attentive tracking depends on the tracking rate. To do this, we quantify how long attention spends dwelling on and shifting between successive items in the tracking display.

Methods

Participants

Seven observers participated in the experiment: 5 observers naïve as to the purpose of the experiment and 2 of the authors. All had normal or corrected to normal vision. All observers gave informed consent prior to participating in the experiment.

Stimuli

Stimuli were displayed on an 18-in. Philips LCD monitor (60 Hz, 1280 × 1024 resolution) controlled by a PC running MATLAB 7.01 using PsychToolbox extensions (Brainard, 1997; Pelli, 1997). The stimulus consisted of 10 clock faces arranged on an imaginary circle at 7° eccentricity from a fixation point (Figure 1A). Each clock subtended about 2.5° of visual angle and featured a single hand making one revolution per second. The clocks were sequentially cued (by changing the rim on the clock from black to red) such that an observer could attentively track the cued clock around the display. The positions of the clocks' hands were chosen such that the hand on the cued clock always moved over the same portion of the clock face while that clock was cued. For example, in a given trial the hands on all the clocks might be set such that the hand on the cued clock always moves from the 3 o'clock to the 4 o'clock position. This time range was chosen randomly at the start of each trial.

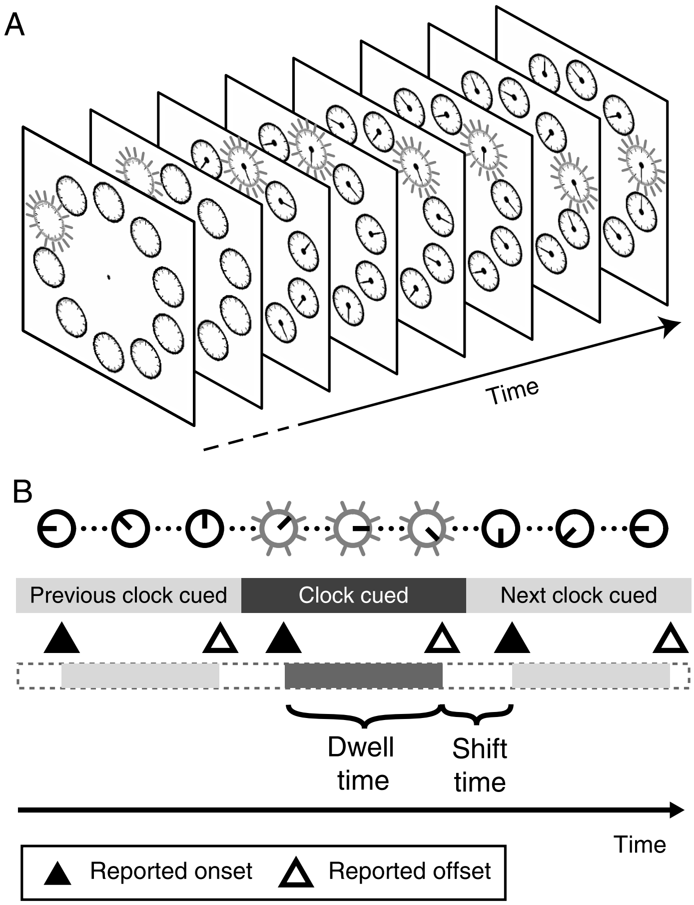

Figure 1. (A) Stimuli used in Experiment 1. Ten smoothly running analog clocks are sequentially cued by changing the rim of the clock from black to red. The times on the clocks are set such that the cued clock always has the same onset and offset time. The dashed line indicates the warm-up period during which no clock hands are visible (time axis not to scale). Click here to view a quicktime movie of a half-speed, continuous version of the stimulus. Click here for sample MATLAB code. (B) Schematic representation of dwell and shift time. The veridical cue durations are shown in the upper row of grey blocks. Observers report the earliest and latest perceived time on the cued clock. The period between these moments, shown as the dark grey block in the lower row, is taken as the attentional dwell time. The time between these periods is taken as the shift time. Together, dwell time and shift time add up to the periodicity of the tracking stimulus—the step time.

Procedure

Observers fixated a point in the center of a blank grey background. At the start of each trial, ten empty clock faces appeared simultaneously. Before the hands appeared in each clock, the empty clock faces were consecutively cued such that observers could start tracking the cued clock at the correct pace (the warm-up phase). After a variable duration, randomly chosen between 500 and 1500 ms, the hands appeared on the clocks, and the critical phase of the trial began. All the clocks were cued once, in order, continuing from the position of the cued clock in the warm-up phase. The task of the observer was to track the red clock and to report, in separate blocks, either the earliest or latest time that he or she perceived in the red clock. After the cue had completed a full cycle, all the clocks disappeared and were replaced by a single, centrally presented clock. Using the keyboard, participants could adjust the hand of the clock to indicate the time they observed on the target clock during the trial, after which a further key logged their report and initiated the next trial. Because the cue completed a full cycle around the array during the critical phase in each trial (i.e., each of the clocks was cued once), observers based their response on an impression accumulated over 10 presentations.

We varied the rate at which clocks were cued: In different conditions, clocks were cued for 67, 100, 133, 167, or 200 ms each. The duty cycle was 100%, such that the offset of the cue at any given clock coincided with the onset of the cue at the next clock. Importantly, the hands on the clocks moved at the same speed in all conditions (1 Hz)—only the duration for which the clocks were cued was varied. The critical phase of each trial therefore varied in duration from 667 to 2000 ms depending on the tracking rate. Observers completed 50 trials in each of 5 tracking rate conditions for a total of 250 trials per block. All conditions within a block were randomly interleaved. Observers completed one block in which they reported the perceived onset of the cue and another block in which they reported the perceived offset, separated by a short break. Each block was preceded by 50 practice trials. Observers were randomly assigned to carry out either the Onset block or the Offset block first—four carried out the Onset block first. The entire experiment took about 90 minutes per observer.

Within each condition, we inspected the distributions of reported onsets and offsets and discarded values more than 3 standard deviations away from the mean. Only 1.3% of trials were discarded in this way. For each condition, the time between the mean onset and the mean offset was taken as a measure of dwell time. The complement of the dwell time, that is, the difference between the step time and the dwell time, was taken as a measure of shift time.

Results

Figure 2 shows the mean shift time as a function of step time across all 7 observers, re-plotted as dwell time in the right panels. A one-way analysis of variance showed a significant effect of step time ($F(4) = 6.82$, $p < 0.001$). Follow-up contrast tests showed that the linear trend evident in Figure 2A is significant ($t(30) = 5.22$, $p < 0.001$): the time it takes to shift attention between clocks turns out to be a constant fraction of step time.

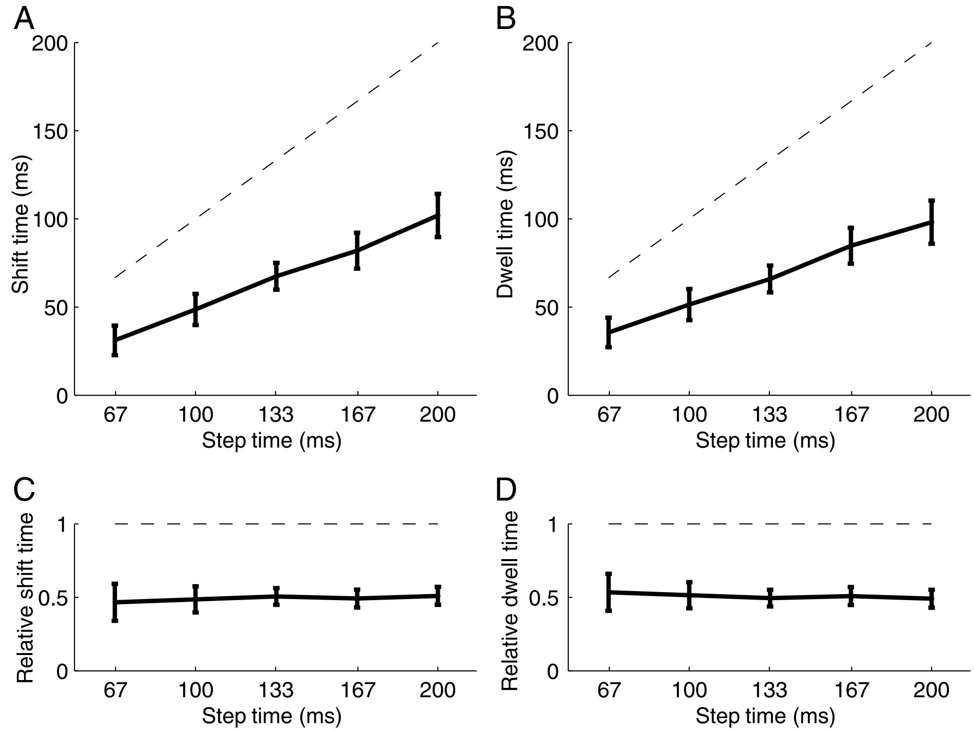

Figure 2. Mean attentional shift time (A) and dwell time (B) for different tracking rates across seven observers. Error bars depict standard errors of the means for seven observers. For comparison purposes, the dashed lines indicate the veridical duration of the cue. The lower plots have been rescaled by step time, showing that shift time (C) and dwell time (D) appear to be constant fractions of the step time.

Figure 3 shows the mean reported onsets and offsets across all observers, plotted as filled and open triangles, respectively. As described above, the period between reported onsets and offsets is the dwell time. Veridical cue durations are indicated by solid dark gray bars, and conditions are plotted such that the mid-points of the durations are aligned. For all step times, reported onsets were later than veridical; that is, attention arrived after the cue appeared. In fact, attention tended to arrive around the half-way point in each condition. Conversely, reported offsets tended to be near veridical, indicating that observers seem to have waited until the cue moved before shifting attention. The center of the dwell time (indicated by small vertical lines) therefore tended to be later than the center of the veridical duration. A one-way analysis of variance showed that the absolute deviation from the veridical center did not depend on step time ($F(4) = 0.38$, $p = 0.82$).

Interestingly, our results show that although it appears to be possible to shift attention from one clock to another in as little as 30 ms, at slower tracking rates significantly more time is lost shifting attention between clocks. Although it is evidently possible for attention to shift very rapidly, it seems that an appropriate external signal is required for it to do so, at least at the rates we tested.

Furthermore, our findings provide indirect support for the notion that attention moves smoothly around the visual field during tracking. A spotlight smoothly moving from location A to B to C at a constant speed will, given that all other factors are equal, lose more time in between locations when moving slowly than when moving quickly. The time cost of shifting attention between locations would therefore be inversely related to the tracking rate, which is evident in our results.

Experiment 2

Although in the previous experiment observers were explicitly instructed to track the cue, we wanted to eliminate the possibility that observers were using an alternate strategy of attending to one location and waiting for the arrival of the cue. To this end, we carried out a control experiment (Experiment 2A) designed to reduce the effectiveness of this strategy. We did this by randomly removing hands from clocks for short periods of time. These periods were chosen at random, independently for each clock face. In this condition, attending to one location and waiting for the cue to arrive is an ineffective strategy, since there is a good chance that the hand will not be visible for the entire duration of the cue at that particular location. Conversely, while tracking the cued clock, the occasional blank clock face is less of an obstacle, since an impression is formed over several repetitions.

We also wanted to ensure that the effect we observed in Experiment 1 was not due to the fact that onset and offset

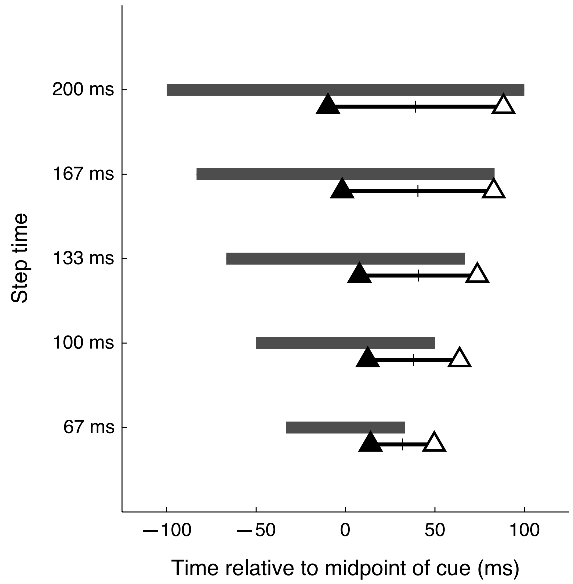

Figure 3. Reported onsets and offsets for all conditions across 7 observers. Dark gray bars depict cue durations, and filled and outlined triangles represent reported onsets and offsets, respectively. Periods between consecutive onsets and offsets, marked by black lines, are taken as the dwell time, with the midpoint indicated by a small vertical line.

reports were collected in different blocks. It is conceivable that due to the slightly different task in the two blocks, observers may have subtly changed their tracking behavior or biased their report. To control for this, we had observers report both onset and offset for each trial, rather than reporting onsets and offsets in separate blocks. At the end of each trial, the response clock featured two identical hands, which the observer could move independently to indicate the range of times he or she observed in the cued clock.

We have previously demonstrated that observers are very accurate at reporting the position of a moving clock hand when they do not need to make attentional shifts (Carlson et al., 2006). However, in the experiments reported here, observers do make attentional shifts, so we carried out an additional control experiment (Experiment 2B) to ensure that the perceived position of the moving clock hand is not biased by some interaction with the moving attentional spotlight. In this control experiment, we randomly varied both the direction in which the cue moved around the array and the direction in which clock hands moved on the clocks. As in Experiment 1, the task was to report, in separate blocks, the counterclockwise and clockwise edges of the sector swept by the clock hand. However, unlike Experiment 1, because the clock hand moved counterclockwise on half the trials, each edge could be either an onset or an offset. Since onset and offset trials were randomly interleaved, this also served as an additional check that the effect observed in Experiment 1 was not a task artifact.

Methods

Participants

Three observers participated in each of the two control experiment: 2 observers naïve as to the purpose of the experiments and 1 of the authors. All had previously participated in Experiments 1 and 3. Participants were selected on the basis of previous experience with attentive tracking, due to the increased tracking difficulty caused by the flashing transients associated with the appearance and disappearance of the clock hands in Experiment 2A. All observers reported that they were able to attentively track the cued clock and form an impression of the time on the clock despite these transients.

Stimuli

The stimuli used in both experiments were identical tothose used in Experiment 1, with the following exceptions:

In Experiment 2A, during the critical phase of each trial, each of the clock hands was randomly absent for periods of 250 ms such that overall, each clock hand was present for only 70% of the total duration of the stimulus. These periods were chosen independently for each clock with the sole restriction that they could not be back-to-back.

In Experiment 2B, we varied both the direction of movement of the cue around the array and the direction of the clock hand on the clocks. The stimuli were otherwise unchanged.

Procedure

The procedure was identical to Experiment 1, with the exception that in Experiment 2A observers reported both onset and offset on each trial. For this purpose, the centrally presented clock at the end of each trial had two hands instead of one, which the observer could independently adjust to indicate an arc subtending between 6 and 120 degrees. Observers were instructed to use this clock to reproduce the range of times they had seen on the cued clock during the trial.

The clock used at the end of each trial in Experiment 2B was unchanged, although observers were made aware that during the trial, the clock hand could move in either direction, and that they were to report either the most clockwise or most counterclockwise hand position they perceived within the cue irrespective of the direction in which the hand was moving (which was thus task-irrelevant). We noticed that, especially at higher tracking rates, reporting the direction of the moving clock hand is

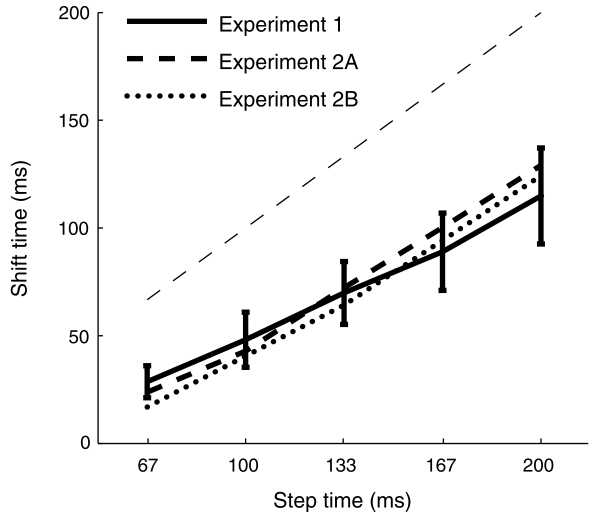

Figure 4. Mean attentional shift time as a function of step time across three observers who participated in Experiments 1, 2A, and 2B. The solid black line indicates results from Experiment 1 (with error bars indicating standard errors of the mean), and the dashed and dotted lines indicate results from Experiments 2A and 2B, respectively.

actually more difficult than reporting either of the two boundaries of the sector it sweeps over. This is because when the hand reaches the end of its sweep, it jumps back to the beginning, giving an impression of motion quite similar to the actual motion of the sweeping hand. In fact, observers reported usually being unaware of the hand's direction, making it unlikely that they were able to (either tacitly or deliberately) bias their response. In Experiment 2B, only three tracking rates (67, 133, and 200 ms step time) were measured.

Results

Figure 4 shows the mean shift time as a function of step time for 3 observers. The dashed and dotted line represents estimates from Experiments 2A and 2B, respectively, with the solid line representing estimates for the same observers from Experiment 1. A 2 × 5 factorial analysis of variance confirms that the results from Experiment 2A replicate those from Experiment 1: There is a significant effect of step time ($F(4) = 11.49$, $p < 0.001$), but no significant difference between experiments ($F(1) = 0.13$, $p = 0.72$) and no significant interaction ($F(4) = 0.16$, $p = 0.96$). A 2 × 3 factorial analysis of variance confirms that the results from Experiment 2B likewise support Experiment 1: There is a significant effect of step time ($F(2) = 22.5$, $p = 0.04$) but no significant difference between experiments ($F(1) = 0.023$, $p = 0.89$) and no interaction ($F(2) = 1.02$, $p = 0.38$).

The results from Experiments 2A and 2B show that the linear relationship between step time and shift time is robust, even when observers report both onsets and offsets in the same trial or interleaved within blocks, and after controlling for possible interactions between the movement of the clock hand and the movement of the attentional spotlight. Together, these experiments indicate that the effect observed in Experiment 1 is not a strategy effect due to task differences between different blocks or a result of bias. Furthermore, because we replicated the results from Experiment 1 despite making it ineffective to attend to just one location, we can be sure that observers are tracking the cued clock with attention.

Experiment 3

In Experiments 1 and 2, we found that attentional dwell time was dependent on the rate at which observers tracked (step time). However, step time co-varied with cue duration: When tracking slowly, each cue was presented for a longer duration than when tracking rapidly. To further probe the relationship between tracking rate and the time course of attention, in Experiment 3 we manipulated the duty cycle of the tracking cue, which allowed us to reduce cue duration without changing tracking rate. In this way, we investigated whether attentional dwell time was dependent on tracking rate or cue duration. In other words, if at a given tracking rate observers only report perceiving 100 ms of a cue lasting 200 ms, how is their percept affected if we reduce the duration of the cue to 150, 100, or even 50 ms?

This manipulation allowed us to investigate whether dwell time was determined by perceptual factors such as flash-lag (MacKay, 1958; Nijhawan, 1994). Independently varying the step time and cue duration made it possible to separate the contribution of moving attention from the contribution of low-level effects contingent on the transients caused by cue onsets and offsets. We conceived of two possible predictions: If dwell time is determined solely by the movement of attention, synchronized to the external cue, we would find little or no effect of duty cycle at constant step time, since the rate at which attention moves remains constant. Conversely, if low-level effects contingent on transients contribute to our estimate of dwell time, we *should* find an effect of duty cycle, since the cue duration is much reduced at lower duty cycles. For example, a possible explanation for the results of Experiment 1 might be the flash-lag effect reducing the visibility of the cued clock for the first half of its total duration. Similarly, although the observers' task is to report a fairly low-level feature (orientation), perceived onsets might have been delayed by some constant amount as a result of attention needing time to begin to encode that feature. If this were the case, we would expect dwell time to be

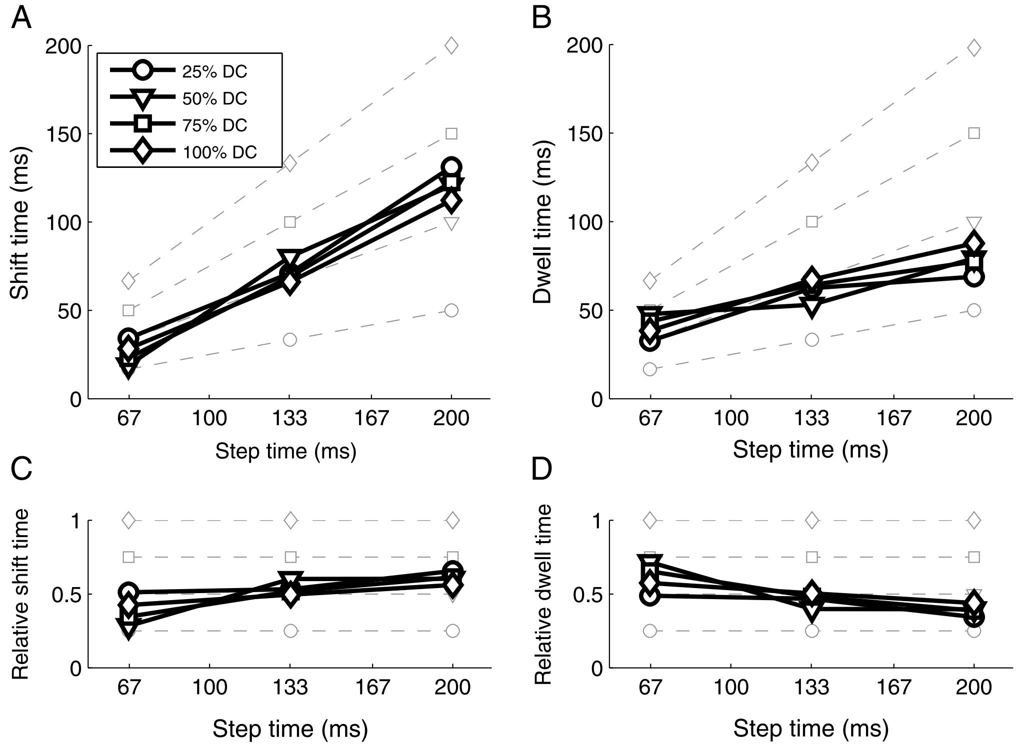

Figure 5. Mean attentional shift time (A) and dwell time (B) as functions of step time for different duty cycles across four observers. For comparison purposes, the dashed lines indicate the veridical duration of the cue for each condition. The lower plots have been rescaled by step time, showing shift time (C) and dwell time (D) as fractions of the step time.

strongly dependent on cue duration (at constant tracking rate) and as such on duty cycle.

Additionally, introducing a blank period between successive cues allowed us to investigate what signals the attentional system uses to maintain pace during attentive tracking. In Experiment 1, cue offsets and onsets coincided, making it impossible to separate whether attention leaves a target as soon as the cue disappears there, or whether attention leaves a target when the cue appears at the next target. By manipulating the duty cycle, we sought to make this distinction.

Methods

Participants

Four observers participated in the experiment: 3 observers naïve as to the purpose of the experiment and 1 of the authors. All had previously participated in Experiment 1.

Stimuli

Stimuli were identical to the stimuli used in Experiment 1 with one exception. The duty cycle of the tracking cue was manipulated for a total of four conditions: 25%, 50%, 75%, and 100%. In the lower duty cycle conditions, the cue offset did not coincide with next cue onset. Rather, the duration of each cue was reduced without increasing the rate at which successive clocks were cued, such that there was no longer a cue present all the time. The effect of this manipulation was to reduce the veridical cue duration without affecting the tracking rate. As in Experiment 1, observers were instructed to report the earliest and latest time they saw in the red clock.

Procedure

The procedure was identical to Experiment 1 with the exception that observers were tested in more conditions. Observers carried out 50 trials in each of 4 duty cycle conditions (25%, 50%, 75%, and 100%), 3 tracking rate conditions (67, 133, and 200 ms steps), and 2 task conditions (report onset or offset) for a total of 1200 trials. The trials within each task condition were randomly interleaved and split into 4 blocks of 150 trials, separated by breaks. Observers were randomly assigned to carry out either the four Onset blocks or the four Offset blocks first—three carried out the Onset blocks first. The experiment took about 25 minutes per block for a total of just under 4 hours per observer.

Shift times and dwell times were calculated based on reported onsets and offsets in each condition similarly to in Experiment 1. Across all observers, 1.2% of trials were discarded for being further than 3 standard deviations from the mean in the respective condition.

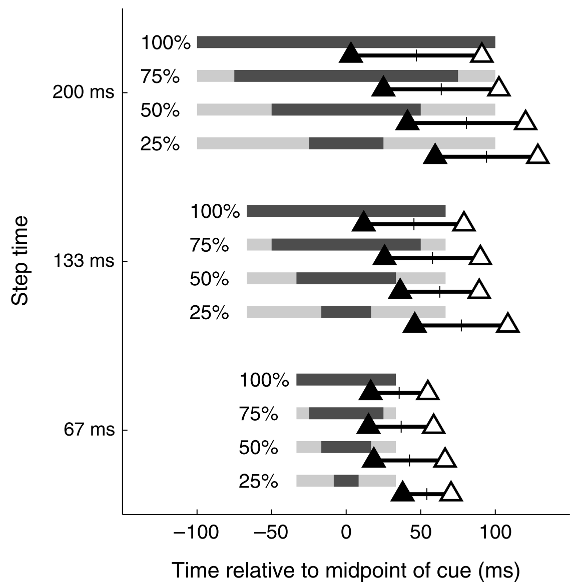

Figure 6. Reported onsets and offsets for 3 step time conditions and 4 duty cycle conditions across 4 observers. Dark gray bars depict cue durations, with light gray bars indicating periods during which no cue was presented. Conditions are plotted such that the midpoints of all cue durations are aligned. Filled and outlined triangles represent reported onsets and offsets, respectively. The midpoint of the period between reported onsets and offsets is marked with a small vertical line.

Results

Estimates for attentional shift time and dwell time as a function of step time and duty cycle for all 4 observers are shown in Figure 5. We carried out a 4 × 3 factorial analysis of variance (4 duty cycles × 3 tracking rates) and found a significant effect of step time on both dwell time and shift time ($F(2) = 6.7$, $p < 0.003$ and $F(2) = 42.7$, $p < 0.001$ respectively). There was no effect of duty cycle ($F(3) = 0.2$, $p = 0.86$) and no interaction effect ($F(6) = 0.2$, $p = 0.97$) on either shift time or dwell time (note that because shift time and dwell time add up to the step time, they are collinear after removing the variance explained by step time). On the basis of these results, the first observation that can be made is that the results from Experiment 3 replicate those of Experiments 1 and 2: We find shift times inversely related to step rate.

Furthermore, our results show that shift time and dwell time are independent of the duty cycle. Apparently, reducing the veridical duration of the tracking cue at a given tracking rate had no effect on the duration for which it was selected by attention. This is evident in Figure 5B—veridical cue durations are shown as grey dashed lines, which the measurements of dwell time clearly do not follow. Perhaps the most remarkable feature of this finding is that the dwell time in the lowest duty cycle condition (25%) is longer than the period of time during which the cue was actually present. The finding that dwell time is independent of duty cycle supports the first of the two alternative predictions put forth earlier: Our measurement of dwell time is contingent on the movement of attention, rather than on perceptual effects such as flash-lag.

Mean reported onsets and offsets are plotted in Figure 6, as filled and outlined triangles, respectively. Veridical cue durations are indicated by dark gray bars, with light gray bars denoting periods during which no cue is visible. We observed that reported onsets and offsets in the 100% duty cycle condition closely replicated reported onsets and offsets from Experiment 1, as expected. Moreover, we found a systematic effect on the center of the reported duration (indicated in Figure 6 as small vertical lines). With decreasing duty cycle, the center of the reported duration shifted away from the center of the veridical duration. A 4 × 3 factorial analysis of variance (4 duty cycles × 3 tracking rates) showed that this effect was significant ($F(3) = 4.71$, $p < 0.01$). This result shows that attention was more strongly locked to onsets than offsets while tracking. Although there was no main effect of step time ($F(2) = 2.90$, $p = 0.13$), we found a significant interaction effect ($F(6) = 4.56$, $p < 0.01$): The effect of duty cycle was proportionally stronger at higher step times (Figure 6). This can be easily understood, since the absolute difference between duty cycle conditions is larger at higher step times.

Discussion

We have presented three experiments exploring the time course of attentive tracking. In Experiment 1, we found an inverse relationship between tracking rate and shift times: Repeatedly shifting attention at a high rate results in shorter attentional shifts. In Experiments 2A and 2B, we verified that this effect was not due to task artifacts or bias and that observers were carrying out the task as instructed. In Experiment 3, we showed that the duration of attentional selection in an apparent motion display is determined by tracking rate, and that during tracking the attention system is locked to stimulus onsets.

Together, our experiments show that during attentive tracking, the fraction of total time spent dwelling on items and shifting between them is constant, irrespective of the rate at which these attentional shifts are made. When a rapidly moving external signal is available, attention can sequentially switch between items remarkably quickly, whereas when the external signal is slower or absent, attentional switches cost correspondingly more time. The periodic engagement of attention seems to only be possible at high rates when a periodic external signal with a similarly high rate is available. The results from Experiment 3 show that cue onsets form the signal to which the moving attentional spotlight synchronizes. Further evidence that the engagement of attention is strongly bound to the periodicity of an external signal comes from the other finding from Experiment 3, namely that the duration for which attention has an item selected is determined only by the tracking rate, irrespective of the actual duration of the cue which the observer is instructed to attend to—even to the point that attention dwells on an item for longer than it is cued.

Our results provide further evidence that the attentional spotlight shifts smoothly during tracking. The spotlight moves around the array of clocks at a constant speed, with each clock selected for as long as it is illuminated. Since the spotlight moves smoothly, at times it will illuminate the area between clocks and no clock will be selected. Clearly, the duration the spotlight spends shining on the area between clocks is dependent on the speed at which the spotlight is moving. Furthermore, since a fast-moving spotlight also moves more quickly over the clocks, the duration of time for which each clock is selected is also briefer such that, irrespective of the tracking rate, the fraction of time for which the spotlight illuminates a clock is constant.

We did not control for eye movements in our experiments. However, previous studies have demonstrated that apparent motion stimuli are tracked without eye movements in trained observers (e.g., Verstraten, Hooge, Culham, & Van Wezel, 2001). Furthermore Experiment 2, in which we greatly reduced the degree to which systematic attentive or ocular saccades might aid an observer on the task, replicated our results from Experiment 1.

In our data, we find very low estimates of attentional dwell time compared to those reported in the literature. We find values between 30 to 100 ms, compared to 200 ms (Moore, Egeth, Berglan, & Luck, 1996) and even 500 ms (Duncan et al., 1994) in previous studies. This might be partly explained by the previously mentioned inconsistent use of the term "dwell time," which often includes the period of time we define as shift time in this paper. Therefore, previous estimates are best taken as upper bounds for the period of time for which attention actually is dwelling on the item. Nonetheless, our findings are supported by observations presented by Cavanagh and Holcombe (2005), who showed observers a circular array of rapidly alternating red and green patches adjacent to patches with leftwards and rightwards tilted lines. At high alternation rates, observers are unable to bind the color of one patch with the orientation of the bars in the other. However, when a moving guide is presented such that the observer can attentively track one pair around the display, the task is much easier. Their interpretation was that the effective temporal resolution of attention was increased during tracking—an observation very much compatible with our low estimates of dwell time during tracking.

It may seem counterintuitive that attention is able to shift from one item in an array to another in as little as 30 ms in one condition, while requiring more than 100 ms to shift between the same items in another condition. However, note that these estimates are well below the lowest shift time estimates from more traditional saccade-like experiments, which lie around 150–200 ms (Carlson et al., 2006; Horowitz et al., 2004). It appears that when tracking a cue that changes location at a higher rate than can be supported using discrete shifts, the attentional spotlight synchronizes to the external cue. This way, the time necessary to repeatedly shift attention short distances in a predictable fashion is much lower. However, the moving spotlight is bound to a velocity, which imposes constraints on its motion. As demonstrated in our third experiment, the spotlight continues to move irrespective of whether the item illuminated by the spotlight is to remain selected or not. Even though the smoothly moving spotlight allows attention to shift nearly an order of magnitude more rapidly than saccade-like shifts, there is a trade-off: More time is lost shifting attention between successive items at lower speeds than at higher speeds.

It would be interesting to see at which tracking rate attention switches from smooth to saccade-like motion. Presumably, the strong linear relationship we found between tracking rate and shift time breaks down at lower tracking rates; it seems unlikely that an observer viewing locations sequentially cued with durations of four seconds would lose two seconds shifting attention between locations. We expect that the time cost of shifting attention while tracking will reach an asymptote at the point where it approaches the time cost of a single, exogenously guided attentional shift—around 140 ms (Carlson et al., 2006).

To conclude, previous studies have found that attention moves smoothly during tracking. Here, we explored the temporal implications of such an account of attentional shifts. Our characterization of the time course of attentive tracking suggests that at high tracking rates, attention synchronizes to an external signal, and that that signal is likely to be cue onset.

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