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Disengaging attention sets the temporal limit of attentive tracking

Jeroen S. Benjamins *, Ignace T.C. Hooge, Maarten J. van der Smagt, Frans A.J. Verstraten

Helmholtz Institute, Experimental Psychology Division, Universiteit Utrecht, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands

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Abstract

At first sight, recent studies investigating the temporal limits of attentive tracking show contradictory outcomes. Attentively tracking an object in an ambiguous apparent motion display can have an upper limit of around 0.4 revolutions per second (rps) [Horowitz, T. S., Holcombe, A. O., Wolfe, J. M., Arsenio, H. C., & DiMase, J. S. (2004). Attentional pursuit is faster than attentional saccade. *Journal of Vision*, *4*, 585–603] or 1 rps [Verstraten, F. A., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research*, *40*, 3651–3664.]. Here, we demonstrate that this difference depends on presentation conditions: an important determinant for the temporal limit of attentive tracking appears to be the duty cycle. Tracking performance at high(er) rates decreases to chance with increasing duty cycle, while at low rates duty cycle hardly has an effect on performance. Results are discussed in terms of (dis)engagement of attention.

Keywords: Attention; Apparent motion; Temporal limits

1. Introduction

In 1912 Wertheimer showed that alternating two frames, each containing a cross in which the cross is rotated 45 degrees in one frame relative to the same cross in the other frame, results in perceiving rocking motion when viewed passively. The perceived direction is ambiguous, since clockwise and counterclockwise motion is equally probable. Attentively tracking one of the spokes of the cross, however, results in a clear apparent motion percept which is called *attention-based apparent motion* (Verstraten, Cavanagh, & Labianca, 2000). This motion percept can also be achieved for ambiguous continuous stimuli like radial gratings (Cavanagh, 1992), a phenomenon known as *attention-based motion perception*.

Recently, several researchers have addressed the question about the temporal limits of attentive tracking. Horowitz and colleagues (Horowitz, Holcombe, Wolfe, Arsenio, & DiMase, 2004) found an upper limit of attentive tracking around 2.5 Hz, whereas Verstraten et al.'s (2000) data suggested a 5–7 Hz limit (Horowitz et al., 2004 express their limit in terms of duration of one frame interval. Their limit lies around a minimum duration of 200 ms, while Verstraten et al. (2000) find a limit of around 70–100 ms). Horowitz et al. (2004) explain this difference by suggesting that the temporal limit of attentive tracking reported by Verstraten et al. (2000) is not a limit of attentive tracking, but rather is a limit of object continuity. In their discussion they suggest that in Verstraten's paradigm observers are merely indexing objects [using FINST (Pylyshyn, 1989) or "object files" (Kahneman & Treisman, 1984)] rather than tracking them using attention. They suggest that, though information about the features is not available, indexing is enough to keep track of an object and is faster than attentional pursuit; only the spatiotemporal history of an object's index needs to be kept track of. However, the spatiotemporal history of the index of an attentively tracked object is ambiguous, whereas the stimuli in the studies on object continuity (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989) are stationary or move unambiguously. An object and thus its index in both attentive tracking paradigms could have moved either clockwise or counterclockwise

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[*] Corresponding author.
E-mail address: j.s.benjamins@uu.nl (J.S. Benjamins).

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between frames with equal probability. Constant attentional selection is thus needed for tracking an object in both Verstraten et al.'s (2000) and Horowitz et al.'s (2004) experiments.

If it is not attentional selection itself, what then constitutes the difference between the temporal limits found by these researchers? Here, we suggest that the differences can be explained by the ability of attention to disengage from one location of a tracked object and engage to the next location of that same object. It is known from both eye movement literature (Fischer & Ramsperger, 1984) and from research on express attentional shifts (Mackeben & Nakayama, 1993) that shifting from one location to another can be faster when previous fixated or attended objects disappear before they reappear elsewhere. In Horowitz et al.'s (2004) experiment offset of one frame and onset of the next coincided, i.e. the duty cycle of each element was 100%. Duty cycle is defined as the duration of one frame expressed as a percentage of the total duration of one frame and a following blank interval. In Horowitz et al.'s (2004) experiment no blank interval was present. The onset of the next frame of placeholders in their attentional pursuit condition triggers attention to make a shift to that next location. Though Horowitz et al. (2004) state that attention does not leave the tracked object, attention still needs to shift from location to location. In contrast, Verstraten et al. (2000) did use blank intervals between two consecutive steps of a tracked object. The duty cycle of a tracked object was 40% in their experiment. Thus, the offset of the tracked object triggered attention to disengage and shift to a next location before the onset of the tracked object at the next location. Here, we therefore manipulate duty cycle systematically.

2. Methods

2.1. Participants

Four observers (three naïve as to the purpose of the experiment) voluntarily participated in the experiment. All had normal or corrected to normal vision. One observer was the first author (JB).

2.2. Stimuli

Stimuli were created and presented using Matlab® 5.2.1 and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) on a Macintosh G4 computer. Stimuli were presented on a 17 inch Iiyama Pro Vision Master 454 monitor set to a resolution of 640 by 480 pixels and a vertical refresh rate of 200 Hz yielding 5 ms timing precision. Participants were placed in a head and chin rest such that the distance to the screen was 86 cm.

Two circular arrays of six evenly spaced discs were alternated in space and time, separated by a blank ISI (except for one condition, see below). One of the two frames containing discs was rotated such that a disc in one frame was located exactly between two other discs in the other frame. The center of the resulting 12 locations a disc in the stimulus could occupy were therefore 30 degrees separated. Discs were white (luminance: 133 cd/m^2) on a gray (luminance: 15.1 cd/m^2) background and had a diameter of 0.5 degrees. The radius of the circular array on which the discs were placed was 4 degrees and was centered around a 4.2 arc minutes black (luminance: 0.26 cd/m^2) fixation point.

Manipulating the duration of the blank ISI gave different duty cycles of the discs: 25%, 50%, 75% and 100%. In the latter case there was no blank interval between the presentations of the two circular arrays, similar to Horowitz et al.'s (2004) attentional pursuit of placeholders. The rate at which these circular arrays alternated was manipulated as well in such a way that discs could travel either at 0.52 or 1.04 revolutions per second (rps). In terms of interval duration (duration of one frame plus following blank interval) this is 160 or 80 ms, respectively. The lower of these rps values approximates the temporal limit found by Horowitz et al. (2004) the other rate is close to the limit found by Verstraten et al. (2000).

2.3. Task and procedure

Tracking in the resulting eight conditions (two levels of rps x four levels of duty cycle) was tested using a response method similar to Horowitz et al. (2004). One of the white discs (random per trial) in the array started out black. This black disc shifted in one of the two possible directions (clockwise or counterclockwise, random per trial). After two full revolutions the black disc turned white and the observers' task was to attentively track this disc. After approximately two more revolutions the alternation of the disc arrays was replaced by probe arrows, presented (0.5 degrees width for 250 ms) at the six locations of the discs. These probes were subsequently masked by six 1 degree stimuli consisting of a constellation of all arrow orientations. These masks were presented for 50 ms (see Fig. 1 for a schematic overview of the sequence). After the presentation of the masks subjects had to report the direction of the arrow presented at the location of the tracked disc using the number pad of the keyboard. Arrows could point in one of eight directions. The arrows at the locations of the other non-tracked discs always pointed in different directions than the target arrow. Each combination of rps and duty cycle was first practiced in a block of 80 trials by each observer. Thereafter, each observer was tested in two blocks of 25 repetitions of each condition (200 trials per block).

3. Results

The results in Fig. 2 (upper left panel) show the mean of the four average proportions correct, calculated per subject (other panels). Individual averages are based on the 50 repetitions per point from the two experimental blocks. For each of the four subjects these results show that at the lower revolution rate of the discs duty cycle has little effect on tracking performance. Subjects can report the direction of the arrow target well above chance performance (0.125). The mean proportion correct responses in the 0.52 rps (160 ms interval duration) condition is 0.90 at 25% and 0.77 at 100% duty cycle. At the higher of the two revolution rates (1.04 rps, 80 ms interval duration) the proportion correct is much more dependent on duty cycle and drops from 0.60 at 25% duty cycle to 0.17 at 100% duty cycle, which is around chance performance. The performance of 60% is expectedly somewhat lower than performance of 66.7% in Horowitz et al. (2004) due to smaller interval duration in the current experiment. The smallest interval duration which yielded 66.7% performance in their experiments was 107 ms.

With increasing duty cycle the last frame containing discs before the probes is presented longer, which possibly results in stronger forward masking of the probes by the discs. However, temporal duration of this last frame is the same at the two revolution rates at some points (e.g. 50% duty cycle at 0.52 rps and 100% duty cycle at 1.04 rps both result in 80 ms duration of the last disc frame), while performance

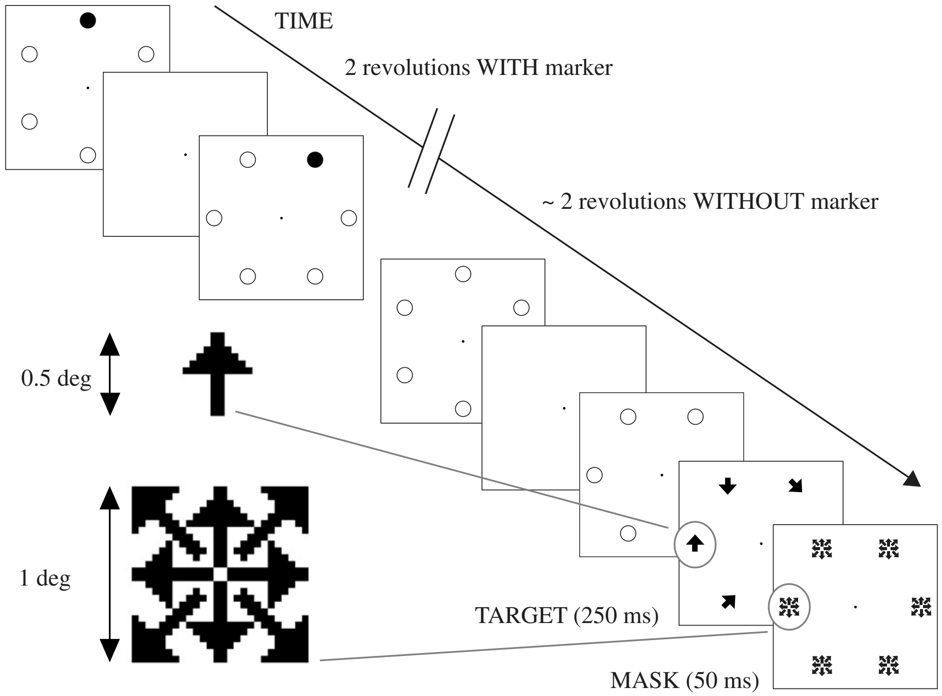

Fig. 1. Schematic overview of the stimulus.

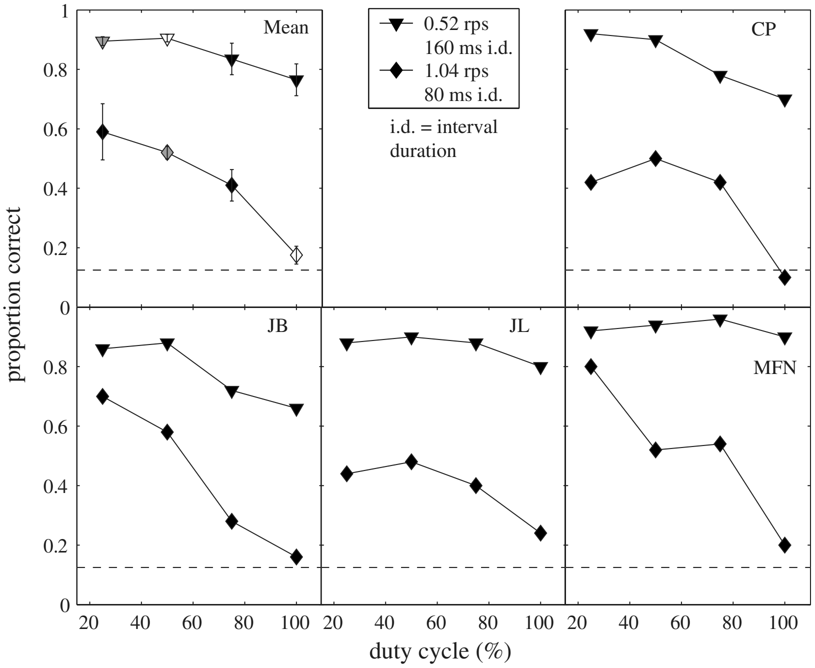

Fig. 2. Upper left panel: average proportion correct (four subjects, error bar = ±1 SEM). Gray markers indicate conditions with same duration of last frame before the probes (40 ms). Analogously white markers indicate conditions where this duration is 80 ms. Other four panels: individual proportions correct (50 repetitions per point). The dashed horizontal lines indicate chance performance.

clearly differs for the two revolution rates at these points (marked gray and white in Fig. 2). Thus, it is unlikely that the effect of increasing duty cycle on performance can be attributed to forward masking.

It could be argued that when tracking becomes more difficult at higher revolution rates of the stimulus, subjects 'miss' or 'skip' an attentional step and are therefore not responding to the disc to be tracked but to the disc at a location before or after the target location. A second analysis shows that subjects did not systematically report the arrows' orientation of one of the other five disc locations. The mean proportion correct stays around chance

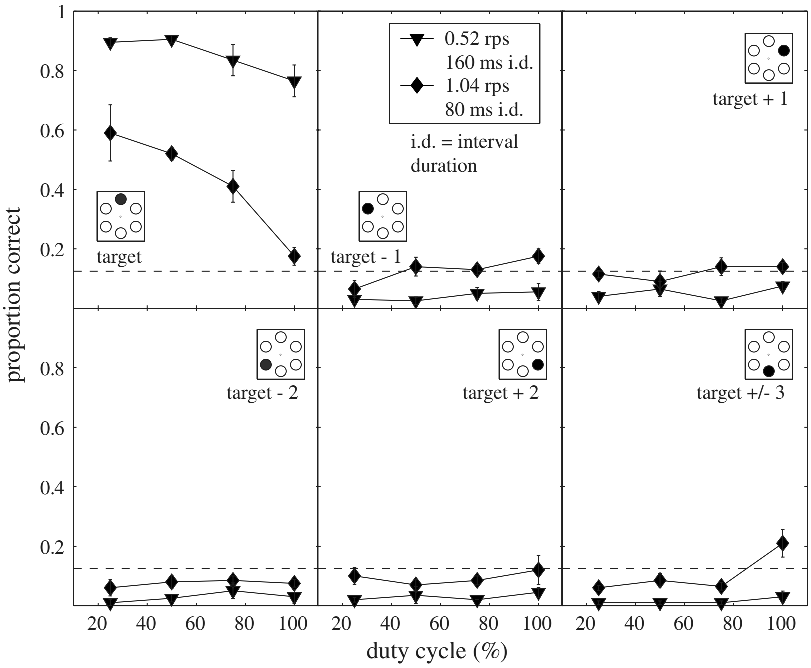

Fig. 3. Average proportion correct (four subjects, errorbar = ±1 SEM) for all discs (target location (upper left panel) and surrounding non-target locations). The dashed horizontal line indicates chance performance.

level (1/8, eight directions to possibly respond to) for all other locations. This can be seen in Fig. 3, where for the target location and all other five locations (expressed as target location plus or minus 1, 2 or 3), the response for all duty cycle and rps combinations stays around the dashed line indicating chance performance. Tracking is just impossible with larger duty cycles at the high revolution rate.

4. Discussion

In the current experiment we have shown that the temporal limit of attentive tracking (or attentional pursuit) of an object in an ambiguous apparent motion display is determined not by the revolution rates of objects in that display per se. It is the duration of a blank interval between the two frames that make up the display that determines whether objects can be tracked at a specific revolution rate or not. More specifically, subjects in our study can track an object at 0.52 revolutions per second (rps), or 160 ms interval duration, independent of the duty cycle (the ratio between duration of one frame with elements and the duration of the following blank interval). For a higher rate (1.04 rps, 80 ms interval duration), subjects can only track an object when the duty cycle of the object is 50% or smaller. At 100% duty cycle tracking performance drops to 17% which is near chance performance (12.5%). Recently, it was reported that attentional pursuit has an upper temporal limit of around 0.42 rps, or 200 ms interval duration, (Horowitz et al., 2004) as opposed to previous results that showed attentive tracking was possible up to revolution rates of around 1 rps, around 80 ms interval duration (Verstraten et al., 2000). Horowitz et al. (2004) explained this difference by suggesting Verstraten et al. (2000) had measured object continuity rather than attentional pursuit. They reasoned that in the latter of the two experiments subjects could just 'index' the to-be-tracked object (Kahneman & Treisman, 1984; Pylyshyn, 1989) and update the spatiotemporal history of that index by means of low-level motion processing. In contrast to these studies (Kahneman & Treisman, 1984; Pylyshyn, 1989), where stimuli were stationary or moved unambiguously, motion of identical objects in both Horowitz et al.'s (2004) and Verstraten et al.'s (2000) paradigm is ambiguous. As argued in the introduction, the spatiotemporal history of the indices belonging to those objects is ambiguous as well. Thus, in both studies constant attentional selection of an object is needed to resolve the ambiguous motion of that object.

With the current results we can now explain the difference found in these studies simply in terms of the temporal layout of the stimulus configuration. In their attentional pursuit condition Horowitz et al. (2004) alternated the two frames with six elements without blank intervals, while in the study by Verstraten et al. (2000) a blank interval was interleaved with the frames which contained the elements. Thus, there was an interval between the offset of an object in one location and the onset of that object in the next location in the latter study. Studies on eye movements and attentional shifts show that moving the eyes or attention to a next location is speeded when the previous fixated or attended object is removed (Fischer & Ramsperger, 1984; Mackeben & Nakayama, 1993). This is explained in terms of the ability of attention to disengage before onset of the next object and thus speeding up (attentional) pursuit or detection of objects. Tam and Stelmach (1993), on the other hand, attribute shorter saccade latencies due to a (temporal) gap between offset of a dot and onset of a target dot not solely to disengagement of attention, but suggest either solely ocular or ocular-attentional disengagement. Klein, Taylor, and Kingstone (1995) have reinterpreted these gap effect results as being solely ocular based. Alternatively, Danckert and Maruff (1997) reinvestigated this gap effect using the original paradigm of covert orienting of visual attention (COVAT) by Posner (1980). Since a gap effect was not found, they concluded that covert attentional processes can only be facilitated when ocular systems are in a disengaged state. For the current experiment, in Danckert and Maruff's (1997) terminology, an ocular system is continuously engaged on fixation, while attention is shifting through multiple locations. If attentional systems are overruled by ocular engagement, we should not have found an effect of our duty cycle manipulation. We therefore suggest that covert attentional mechanisms operate independently from ocular systems, making attentional (dis)engagement possible while ocular systems are engaged.

A further question is whether the disappearance of objects (the offset) act as a cue for attention to shift to another location or that disappearance works differently in determining the speed of attention shifts. Mackeben and Nakayama (1993) already tested this 'readiness/alerting hypothesis' and found that removing an object before target onset shows speeding of attentional shifts, whereas using other cues like a change in fixation mark or shortly increasing brightness of the screen does not. Apparently, element offset does not act in the same way as a cue. It is the timing of disappearance of an object that determines the rate of attentional shifts.

In sum, this study shows that the temporal limits of attentive tracking depend on duty cycle, which facilitates attentional disengagement independently from ocular systems.

Acknowledgments

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