

The speed of visual attention: What time is it?

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The time course of visual attention has been studied using a number of experimental designs. Here, we present a refined version of a technique first used by Wundt more than a century ago and demonstrate it as an effective method to measure the speed of visual attention. The method generates precise and robust data quickly and is flexible enough to be adapted into a variety of established paradigms. In the experiment, participants view an array of moving clocks and report the time on a target clock, which was indicated by a peripheral or central cue. We found latencies of around 140 ms when the target was cued peripherally and latencies of around 240 ms when the target was cued centrally. These values are in good agreement with previous literature and support the validity of the technique as a way to measure the speed of visual attention.

Keywords: visual attention, speed of attention, complication clock

Introduction

There is considerable literature that covers how attention can be covertly directed to particular stimuli or spatial locations. The temporal characteristics of attentional (re)deployment have been the topic of a substantial body of research dating back to the beginning of the previous century and are fundamental to the study of attention because the speed at which the focus of visual attention can be shifted imposes constraints on theories of spatial attention. Indeed, estimates of the speed of attention play a central role in the serial and parallel processing debate (Duncan, Ward, & Shapiro, 1994) and in the relationship between overt and covert attention (Mackeben & Nakayama, 1993).

Some of the earliest reports on the time course of attention were carried out by Wilhelm Wundt using his complication-clock apparatus (Wundt, 1883). The apparatus consisted of a pendulum (later an analog clock; see Figure 1) that participants used to report the time that coincided with some other event such as the ringing of a bell. More recently, the speed of visual attention has been studied using a number of different paradigms including orienting, attentional gating, and visual search.

In orienting experiments, a target is to be reported at one of a varying number of locations. A precue that

indicates the target location is presented at different times before target onset. The time necessary to shift attention is estimated from the function relating performance or reaction time to stimulus onset asynchrony (SOA). Posner (1980) motivated a distinction between exogenous or peripheral cues, which are presented at target location, and endogenous or central cues, which are usually presented at fixation and symbolically represent the cued location. Exogenous cues have been claimed to automatically draw attention (Jonides, 1981), whereas endogenous cues require volition. An important aspect of endogenous cues is that they can vary on the level of processing necessary to decode their meaning, which can influence the timing of the attentional shifts (Eriksen & Collins, 1969). Peripheral cues are consistently found to result in faster attentional shifts than central cues (e.g., Eriksen & Collins, 1969, Müller & Rabbitt, 1989).

In experiments using attentional gating, a term coined by Reeves and Sperling (1986), rapid serial presentation streams (RSVP) were presented in two locations. Participants monitor one stream for a target, such as a letter in a stream of digits, and then shift their attention to the other stream and report the first stimulus they perceive. The time cost of the attentional shift can be inferred from the delay between the reported stimulus and the trigger stimulus. In a variation of this experiment, Weichselgartner and Sperling (1987) used a single RSVP,

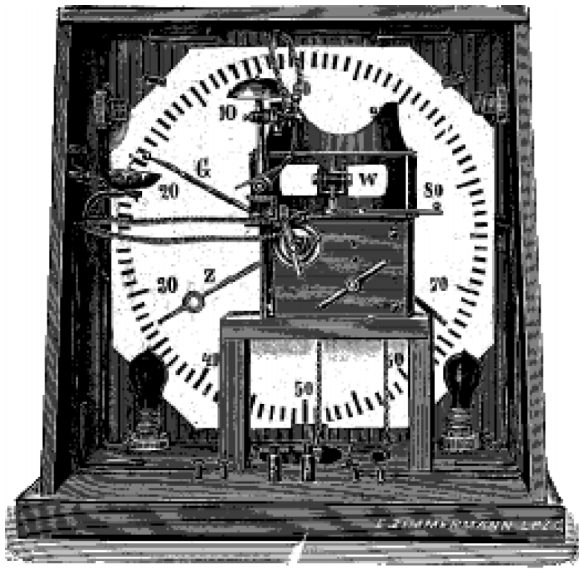


Figure 1. Wundt's complication-clock apparatus. Source of illustration: Zimmermann (1928).

wherein the trigger was a luminance transient. These two experiments could be interpreted as involving endogenously and exogenously cued attentional shift, respectively, and indeed, faster shifts were reported in the exogenous case.

A third approach to measuring the speed of attention is using visual search tasks. In visual search tasks, a target is presented along with a variable number of distracters, and participants report some aspect of the target item. Varying the number of distracters usually leads to a linear increase in reaction time, with the slope of this function being a measure of the time cost of each attentional shift. Two important assumptions of this method are that stimuli are processed serially (not at all an undisputed assumption—see McElree & Carrasco, 1999) and that other mental processes do not interact with the number of items in the array. Visual search experiments, like orienting and attentional gating experiments, report longer shift times when attentional shifts are endogenously controlled than when they are automatic (Wolfe, Alvarez, & Horowitz, 2000).

Quantitative results from previous studies show only modest agreement: Shift times ranging from 33 to 500 ms have been reported. However, giving due consideration to methodological variations between studies and implications of different techniques does reveal a general pattern in the results.

The orienting method is probably the most commonly used method to measure the speed of attention (Posner, 1980). Using a central-cue paradigm with letters as targets, Eriksen and Collins (1969) estimated a shift time of a little more than 200 ms. In an experiment designed mainly to investigate spatial properties of attention, Kröse and Julesz (1989) found a benefit of peripheral cues from SOAs of around 100 ms and above. Nakayama and

Mackeben (1989) estimated shift times of between 70 and 150 ms using peripheral cues in a visual search display. Müller and Rabbitt (1989) extensively tested the automaticity and interference of central and peripheral cues and found maximum cueing benefit for central and peripheral cues at around 275–400 and 175 ms SOA, respectively. Generalizing across orientation studies, peripheral cues seem to involve shift times of around 75–175 ms, with centrally cued shifts taking between 200 and 300 ms.

A major limitation of orienting studies is that the estimate of shift time is linked to performance measures. That is, attention is said to have “arrived” at a particular location when performance reaches some arbitrary threshold, which can lie anywhere between above chance to ceiling. This is perhaps most evident in the experiment reported by Saarinen and Julesz (1991), who flashed digits at random locations in the visual field. They found above-chance identification performance (56% correct) at ISIs as short as 33 ms. In the same experiment, if the performance threshold had been set to 80% correct, then the estimate for the time to shift attention would have doubled to 67 ms. Clearly, the choice of performance threshold influences the estimate of shift time.

Typical estimates of attentional shift time in visual search experiments are on the order of 50 ms (e.g., Wolfe, 1998). However, as noted before, there is some evidence to suggest that the assumed serial processing may be at least partly parallel, which would result in an underestimation of shift time. Another problem inherent in using visual search tasks to estimate the speed of attention is that distracters can vary on the degree of processing necessary to reject them. This introduces variation in the estimate of attentional shift time. In an interesting variation on the classical visual search paradigm, Wolfe et al. (2000) compared the speed of free and directed search strategies. Participants viewed a flickering visual search array searching for a target. When the order in which they were to inspect the targets was constrained, a shift time of 200–350 ms per item was found, as compared with just 100–200 ms when participants freely inspected the arrays. Although it would perhaps be reaching to describe these two conditions as endogenously and exogenously guided, it is clear that allowing attention to reflexively orient results in faster shift times than when it is directed by volition. The mere fact that the participants' search strategies can have such pronounced effects on the estimated shift times is another disadvantage of using visual search tasks to study the time course of attention.

Reeves and Sperling (1986), and later Weichselgartner and Sperling (1987) used the attentional gating paradigm to measure the speed of visual attention. Two RSVP streams were presented, and the estimated time to shift from one RSVP stream to the other in response to the detection of a target letter was found to be around 300–500 ms. Interestingly, Weichselgartner and Sperling, in the second experiment of their study, used a single RSVP

stream with targets indicated by changes in luminance and found that participants tended to report stimuli presented either within the first 100 ms after the cue or at least 300 ms after the cue. With additional manipulations, the experimenters showed that they could affect the two parts of the bimodal distribution independently. They explained their results in terms of two consecutive attentive processes: an automatic fast process (less than 100 ms) and an effortful, slow process (more than 200–300 ms). Assuming that these processes correspond to conditions that are exogenously and endogenously cued, respectively, their findings match the emerging pattern.

There are several limitations of the attentional gating paradigm, particularly when RSVP streams are used. First of all, the presentation rate of the RSVP stream imposes a discrete limit on the response because consecutive characters mask each other. Secondly, identification of the target character recruits higher level object recognition and language functions, which are undesirable as these might well interact with the attentional systems that are being studied. When using RSVP streams, furthermore, results are complicated by the attentional blink phenomenon (Shapiro et al., 1997), especially when both the trigger and the response are alphanumeric characters. Indeed, the bimodal distribution reported by Weichselgartner and Sperling (1987) is reminiscent of response distributions reported in attentional blink experiments.

It seems that there is ample evidence to support a distinction between exogenously or peripherally guided shifts of attention and endogenously or centrally guided shifts of attention based on a variety of methodologically different studies. However, there is considerable variation in the quantitative results reported in the literature. In the current experiment, we report a very simple and precise method to estimate the speed of attentional shifts and apply it to estimate the duration of exogenously and endogenously cued attentional shifts.

The method we used was a refined digital version of Wundt's complication clock, the apparatus first used in some of the first studies on the time course of attention. Participants view an array of moving clocks and report the

time on one of the clocks when it is cued by one of a number of different types of cues. This technique resolves a number of issues faced by other methods. First, it measures time directly rather than inferring it from changes in performance thresholds. It does not recruit higher level processes and does not seem to be dependent on the participants' response strategy. Finally, the response measure is effectively continuous because the hands of the clock are not self-occluding; hence, it avoids the discrete response problem inherent in RSVP tasks.

The experiment tested three conditions. Two conditions tested the speed that observers could orient their attention using peripheral and central cues. The third was a baseline condition used to determine the level of accuracy for making judgments when attention was directed to a location in advance of the cue.

Methods

Participants

Four participants took part in the experiment. All had normal or corrected-to-normal vision. All participants gave informed consent prior to participating in the experiment.

Stimuli

Stimuli were displayed on a Dell LCD monitor (60 Hz, 1,024 × 768 resolution) controlled by a PC running MATLAB 7.1 (The MathWorks, Inc.) using PsychToolbox extensions (Brainard, 1997; Pelli, 1997). The stimulus consisted of 10 clock faces arranged in a circle at 7° eccentricity from a fixation point. Each clock subtended about 2.5° of visual angle and featured a single hand making 1 revolution per second (see Figure 2). The initial

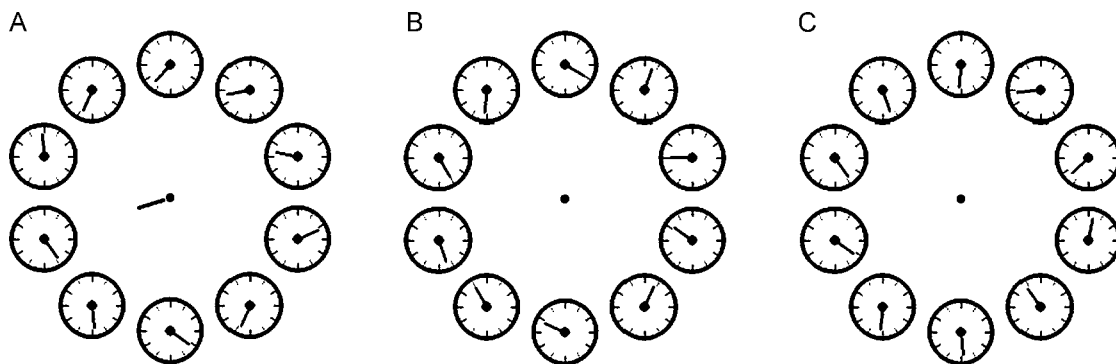


Figure 2. Movies of single trials for the three conditions tested. (A) Baseline condition. (B) Peripheral-cue condition. (C) Central-cue condition. Click on each image to view the corresponding movie.

position of the hand on each of the clocks was randomly determined at the start of each trial.

Procedure

Participants fixated a fixation point in the middle of a blank background. At the start of each trial, all 10 clocks appeared simultaneously. A randomly selected hand position (i.e., time) was selected as time zero (Tz). At Tz, one of a number of cues was shown to indicate one of the clocks. The participants' task was to judge the time on the relevant clock. After a short delay, the clocks disappeared and were replaced by a single, centrally presented clock. Using the keyboard, participants could adjust the hand of the clock as they wished to indicate the time on the target clock they observed during the trial, after which a further key press indicated their satisfaction.

We tested three conditions: a baseline condition, a peripheral-cue condition, and a central-cue condition (Figure 2). In all conditions, the participants' task was to report the time on the clock at a randomly selected time (Tz). In the baseline condition, a line extending from the fixation point to one of the clock positions was presented before each trial; thus, participants were aware ahead of time which clock would be tested. At Tz, the rim of the cued clock would change from black to red. In the peripheral-cue condition, the relevant clock was

indicated at Tz by the outer rim of the clock changing color from black to red. In the central-cue condition, the relevant clock was indicated at Tz by a line extending from the fixation point to the clock. The transient marking Tz was always presented for 83 ms. Participants carried out 6 practice trials followed by 50 test trials for each condition.

Mean latencies between Tz and the time reported by the participant after each trial were calculated for each condition for each participant. Latencies greater than 3 *SD* from the mean were discarded from the analysis.

Results and discussion

Figure 3 shows results for all four participants. Notably, participants performed very near veridical in the baseline condition. This condition serves as a critical baseline for the two conditions in which an attentional shift is necessary. In the two remaining conditions, we found a strong and robust effect of cueing condition on the latency between the actual and reported onset times. Latencies for a shift with a peripheral cue were around 140 ms, and a latency of around 240 ms was obtained with a central cue. These values are in good agreement with the range of values reported in earlier studies using exogenous and endogenous cueing paradigms.

It is interesting to note that with the possible exception of S3, participants were very accurate at reporting the time

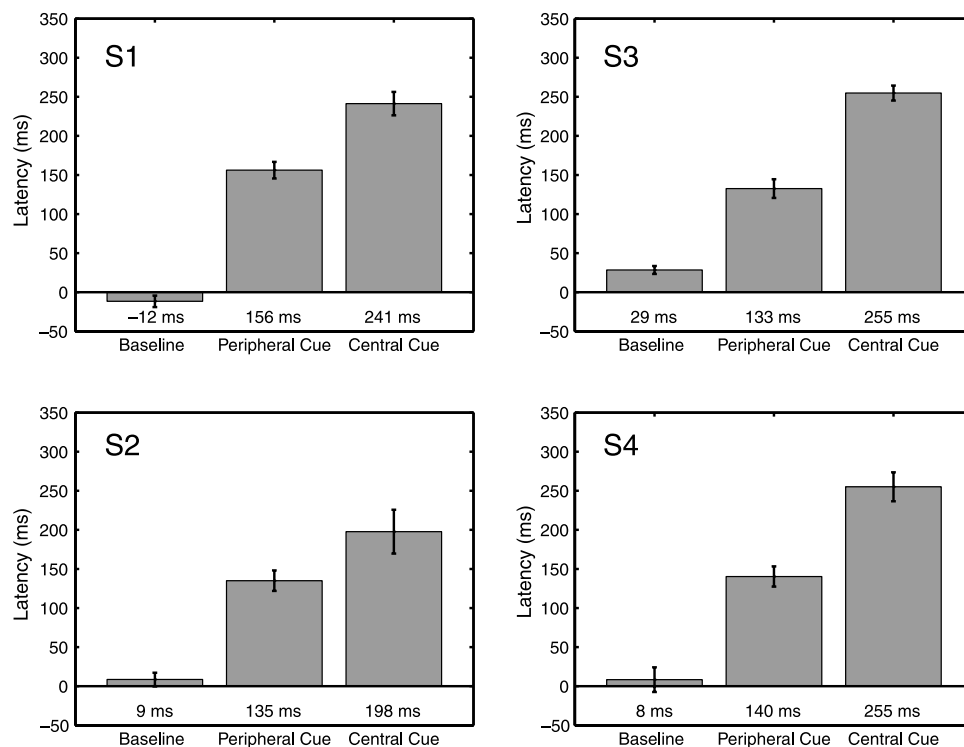


Figure 3. Attentional latencies for four participants in baseline, peripherally cued, and centrally cued conditions. Error bars depict standard errors of the mean.

on the cued clock when they were informed in advance of the to-be-attended location. This indicates that the task was not perceptually challenging and that the latencies measured were accurate estimates of the time that attention arrived on a particular object or location (in this case, the relevant clock). As an aside, it is also interesting to note that the baseline condition is similar to conditions previously observed to generate a flash lag effect (Patel et al., 2000), yet we observed little or no lag in the reported times.

We obtained strikingly similar estimates of shift times in all four participants, particularly in the exogenously cued condition where participants fell within a 23-ms range. Because the response variable in the current experiment is nearly continuous, much more precise data can be acquired in far fewer trials than when using performance measures in orienting paradigms or discrete responses in attentional gating experiments.

Another advantage of the stimulus, and at the same time an interesting avenue for further research, is that the current experimental design can be easily adapted to an attentional tracking experiment, allowing for a comparison of estimates of the speed of attention derived from attentional tracking experiments (Horowitz, Holcombe, Wolfe, Arsenio, & DiMase, 2004; Verstraten, Cavanagh, & Labianca, 2000). Horowitz et al., for example, rather than attempting to measure the duration of single shifts of attention, measured the pace at which observers could make successive shifts in a predictable order. Interestingly, they found relatively slow rates: 200–250 ms during attentional pursuit (most analogous to exogenous cueing) and 300–500 ms for what they call attentional saccades (in the absence of an exogenous guide). Although these values lie far above results from earlier literature and those of the present study, they clearly show a similar pattern.

We believe that the method presented here has great potential for studying the speed of visual attention. A refinement of a century-old technique, the method provides precise and robust results after even a small number of trials. It avoids relying on any high-level processes such as character identification and is flexible enough to be comparable to the established paradigms for measuring the speed of attention.

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