

Attentional selection of noncontiguous locations: The spotlight is only transiently “split”

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It is still a matter of debate whether observers can attend simultaneously to more than one location. Using essentially the same paradigm as was used previously by N. P. Bichot, K. R. Cave, and H. Pashler (1999), we demonstrate that their finding of an attentional “split” between separate target locations only reflects the early phase of attentional selection. Our subjects were asked to compare the shapes (circle or square) of 2 oddly colored targets within an array of 8 stimuli. After a varying stimulus onset asynchrony (SOA), 8 letters were flashed at the previous stimulus locations, followed by a mask. For a given SOA, the performance of subjects at reporting letters in each location was taken to reflect the distribution of spatial attention. In particular, by considering the proportion of trials in which none or both of the target letters were reported, we were able to infer the respective amount of attention allocated to each target without knowing, on a trial-by-trial basis which location (if any) was receiving the most attentional resources. Our results show that for SOAs under 100–150 ms, attention can be equally split between the two targets, a conclusion compatible with previous reports. However, with longer SOAs, this attentional division can no longer be sustained and attention ultimately settles at the location of one single stimulus.

Keywords: attention, divided spotlight, time course, premotor theory

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Introduction

The processing of a full scene in parallel up to a high level description of each of the objects it contains is an overwhelming task for our brains. The mechanism in charge of reducing the perceptual load according to behavioral constraints is termed “selective attention.” It is not clear at which stage of sensory processing it operates (Driver, 2001). A classical metaphor for selective spatial attention is that of a spotlight shining on some part of the visual field (Crick, 1984; Eriksen & Eriksen, 1974; Eriksen & St James, 1986; Eriksen & Yeh, 1985; LaBerge, 1983; Posner, Snyder, & Davidson, 1980; Tsal, 1983). This widely used image naturally leads one to wonder whether the attentional spotlight is necessarily undivided or whether it can be split,

thereby allowing the brain to process in parallel two or more noncontiguous foci. In recent years, evidence that multiple locations can be simultaneously attended has accumulated (Awh & Pashler, 2000; Baldauf & Deubel, 2008; Bichot, Cave, & Pashler, 1999; Carlson, VanRullen, Hogendoorn, Verstraten, & Cavanagh, 2007; Gobell, Tseng, & Sperling, 2004; Godijn & Theeuwes, 2003; Kraft et al., 2005; Kramer & Hahn, 1995; McMains & Somers, 2004, 2005; Müller, Malinowski, Gruber, & Hillyard, 2003; Pylyshyn & Storm, 1988), though most studies lack the temporal resolution necessary to distinguish between a truly split spotlight enhancing multiple locations in parallel and an undivided one switching quickly between concurrent locations (Townsend, 1990; VanRullen, Carlson, & Cavanagh, 2007).

A seemingly convincing argument in favor of a divided spotlight was made by Bichot et al. (1999). They

presented human subjects with eight shapes arranged on a circle, two of which—the target shapes—were of a different color than the remaining distractor shapes. After a delay (105 ms), they briefly (60 ms) presented letters inside the shapes, followed by a mask. The primary task of the subjects involved a shape judgment on the target shapes, ensuring that attention was effectively directed to them. The secondary task was to report as many letters as possible from distractor and target locations alike. The probability of correctly reporting the letter inside a shape was used as a proxy for the amount of spatial attention that was allocated to that location. The authors reported that:

1. attention was preferentially allocated to target locations over distractor locations;
2. given that a letter at a target location was reported, the other target location still enjoyed a greater letter report probability than distractor locations;
3. letter report at distractor locations intervening between the two targets was not better than at other distractor locations.

As the letter presentation time (60 ms) was not deemed long enough for the spotlight to switch from one location to another, they concluded that the spotlight must have been divided between the two targets without encompassing distractor locations between them.

While their argument appears strong, it relies in part on an inadequate use of conditional probabilities. The reasoning flaw is best understood through a numerical example. Consider a situation in which no attentional split occurs, so that only one of the two targets receives attention (letter report probability of 0.6) while the other is processed at the same level as a distractor (letter report probability of 0.2). This yields an overall probability for reporting a letter at a target location of 0.4. The calculation performed by Bichot et al. (1999) based on conditional probabilities would conclude that, given that a letter was correctly reported at one target location, there is a 0.3 probability ($= 2 * 0.6 * 0.2 / (0.6 + 0.2)$, see [Methods](#) section) of correctly reporting a letter at the other target location, against 0.2 at a distractor location. Hence, they would reach the erroneous conclusion that both targets simultaneously received attentional resources above the distractor level. To summarize, the argument put forward by Bichot et al. (1999) is inconclusive, and the possibility remains that attention was not divided between the two simultaneous target locations in this paradigm. There exists however a proper way to analyze data collected with this paradigm, which determines the probability of letter reports at the most and least attended target locations, not from conditional probabilities but through the resolution of a simple second-degree equation (see [Methods](#) section). With access to these two probabilities, conclusions can be drawn about the integrity or split of the spotlight. In this

paper, we present a replication of Bichot et al.'s (1999) experiment, which we analyze in this novel way; in addition, by varying the delay between the presentation of the shapes and the appearance of the letters, we are able to track the deployment of the attentional spotlight(s) over time. We find that for delays under 100–150 ms, attention can be equally split between the two targets, a conclusion compatible with previous reports. However, with longer delays, attention ultimately settles at the location of one single stimulus.

Methods

Subjects

Nineteen subjects participated in this study: 8 females, age range 18–32, mean 22.3; 11 males, age range 22–34, mean 26.2. Four out of our 19 subjects performed an insufficient number of trials (less than 25 trials per SOA were left after all discards mentioned later on). The following analysis thus includes only 15 subjects.

All subjects had normal or corrected-to-normal vision, including normal color perception. Subjects provided informed consent before starting the experiment and received financial compensation afterward. The experimental procedure received IRB approval from the California Institute of Technology.

Apparatus

Subjects were seated in a dark room specially designed for psychophysics experiments. The eyes were approximately 120 cm from a computer screen ($1,024 \times 1,286$ pixels, 3×8 bit RGB), connected to a Silicon Graphics (Mountain View, CA) O2 computer running a custom-made OpenGL software. The refresh rate of the monitor was 75 Hz, and the display was synchronized with the vertical retrace of the monitor. Black and white luminances were set to the minimum and maximum values achievable by the monitor.

Experimental procedure

We closely followed the paradigm used by Bichot et al. (1999). Before starting the experiment, subjects were given written instructions and a number of practice trials. Each subject was given a particular target color (red or green): 8 subjects searched for red targets among green distractors, 11 searched for green among red. Subjects had 1 hour to complete the task, including the practice trials (except for subjects who were tested on 7 SOAs, who completed two

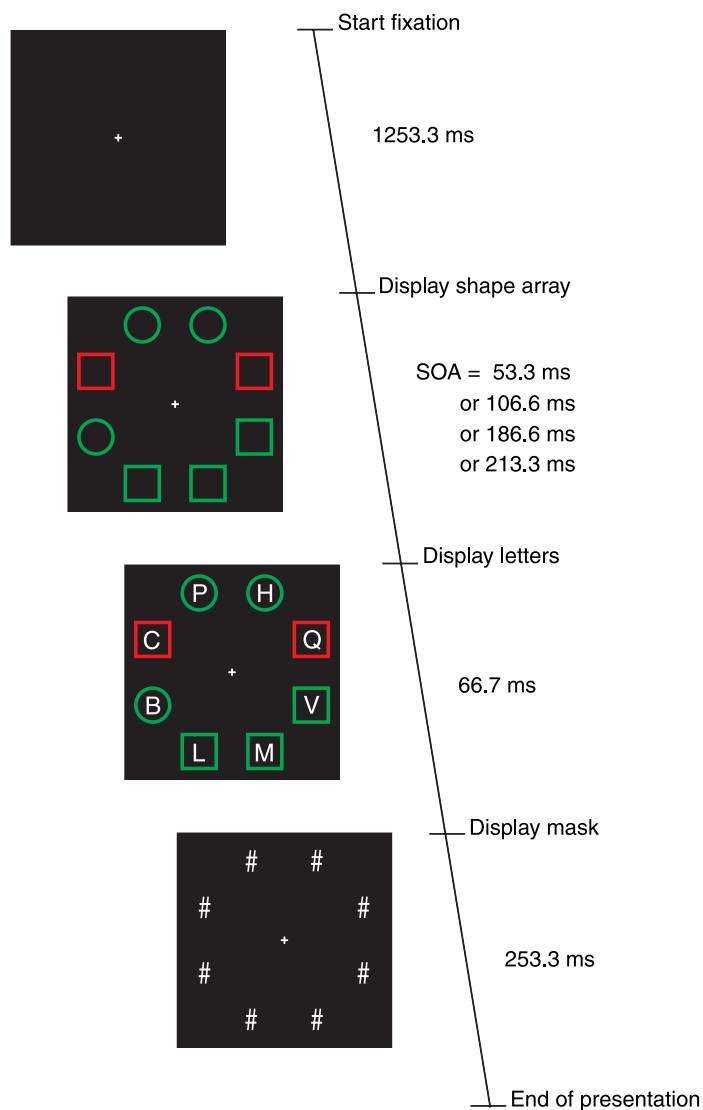


Figure 1. Stimulus sequence for one trial. The primary task consisted in comparing the shapes of the two odd-colored items (targets). The secondary task involved reporting as many letters as possible from the subsequent array. The letter report probability was used as an indication of the amount of attention allocated to the corresponding location. The use of variable stimulus onset asynchronies (SOAs) between the onsets of the shape and letter arrays allowed us to investigate the time course of attentional deployment.

1-hour sessions). Therefore, different numbers of trials were collected for the different subjects, and the different trial types were fully randomized. The sequence of displays in this experiment is shown in Figure 1.

The background was black. Each trial began with the presentation of a central fixation cross that the subjects were instructed to fixate during the entire duration of the trial. The instructions explicitly warned against eye movements. After a delay of 1200 ms, the primary

stimulus display was presented. It contained a circular array of eight shapes, two of which were of the target color and the remaining six of the distractor color. The shapes were equally spaced on an imaginary circle with a radius of 4.8 degrees of visual angle centered on the fixation cross. To avoid potential confounds associated with having stimuli on horizontal and vertical midlines, all the shapes were placed so that each shape was 22.5 degrees off a horizontal or vertical midline. The primary stimulus shapes were either unfilled circles (2.1 degrees visual angle diameter) or unfilled squares (2.1 degrees visual angle across). In half the trials, the two target shapes were the same (and of those trials, half had two circles and half had two squares); in the other half of the trials, the two target shapes were different (one was a square and the other was a circle). Among the six distractor shapes, three were circles and three were squares, randomly assigned. In each trial, the two targets could be either adjacent to one another or separated by one, two, or three distractors. All four target separations were equally likely to occur, and across trials the two targets were presented at all possible locations on the imaginary circle. The target separations, as well as the target positions, were selected randomly across trials so that the subjects could not anticipate a particular display configuration. The primary task was to determine whether the two target shapes were the same or not. It was emphasized that the primary task had to be performed correctly for the trial not to be discarded. Since a failure to perform the shape comparison task might potentially reveal an attentional wandering, only trials for which the subjects correctly performed the primary task were considered for further analysis.

After a variable stimulus onset asynchrony (SOA), eight white letters were presented, each centered within one of the shapes. We started out with seven SOAs: 0, 40, 53.3, 80, 106.6, 160, 186.6, and 213.3 ms. After running 7 subjects and looking at the data, we reduced this number to four SOAs: 53.3, 106.6, 186.6, and 213.3 ms in order to limit the required number of trials per subject. Only the 4 SOAs that were common to all subjects are considered in the following analysis. The responses to a probe at a particular SOA may vary depending on which other SOAs the subject is exposed to on other trials; likewise, extra practice or fatigue may entail differences in the responses across these two subject groups. We initially performed all subsequent analyses with a factor for the subject's group. As no main effect of the group nor any interaction was ever found, we decided to consider that all subjects came from the same population, and dropped the factor group, so as to provide the reader with a less complex picture. The letters were chosen from all possible consonants but V, W, X, and Z for the 7-SOA group, and from all possible consonants for the 4-SOA group; no two letters were the same in a given trial. Each letter subtended a visual angle of 0.6 degrees vertically and 0.4 degrees horizontally. The secondary task was to report as many letters as possible. Both shapes and

letters were removed 66.7 ms after letter onset, simultaneous with the presentation of masking stimuli consisting of a pound (#) sign (same size as letters) at each of the locations previously occupied by the letters. Masking stimuli were used to prevent further processing of the letters from iconic memory after their removal. After a 240-ms delay, a display containing all possible letters appeared on the left of the screen, and using a mouse, the subjects selected any number of letters they had seen, from zero to eight. They were encouraged to report letters even if they were not certain of their presence but were warned against any wild guesses. After clicking on the letters (secondary task), they had to click on one of two buttons presented on the right-hand side of the display, “same” or “different,” referring to the target shapes (primary task). The importance of accuracy over speed was emphasized.

Probability estimates

In the following, let T1 be the event “the letter at the most attended target location is reported” and let T2 be the event “the letter at the least attended target location is reported” (of course, this definition is only for mathematical purposes and does not preclude the possibility that in practice both target locations might receive comparable amounts of attention). We assume that the probability of reporting a behaviorally relevant target only depends on the amount of attention that it receives. It follows that the events T1 and T2 can be considered independent. Let BOTH be the event “both target letters are reported,” and let NONE be the event “none of the target letters is reported.”

Conditional probabilities

Let us first examine how Bichot et al. (1999) computed conditional probability estimates. For each trial, when a letter at a target location was correctly reported, they considered each other location in turn (the location adjacent to the correctly reported target and closest to the second target was assigned position 1, and position number was incremented moving away from the correctly reported target around the circle) and incremented a counter if the letter at that location was correctly reported. In trials with two correctly reported targets, they applied this procedure twice, i.e., for each target in turn. After going through all the trials, the final counts for each position were divided by the number of correctly reported target letters to obtain the conditional probability estimates. In this procedure, the conditional probability of reporting the other target letter given that one target letter is reported is thus given by $2 \cdot N(\text{BOTH}) / (N(\text{T1}) + N(\text{T2}))$, which can also be written as $2 \cdot P(\text{BOTH}) / (P(\text{T1}) + P(\text{T2})) = 2 \cdot P(\text{T1}) \cdot P(\text{T2}) / (P(\text{T1}) + P(\text{T2}))$. As described in the [Introduction](#) section, this procedure can artificially foster the conclusion that both targets are simultaneously

attended, even when only one of them actually receives prioritized processing.

Target locations

Our improved analysis method, described below, does not rely on the use of conditional probabilities. For simplicity, P(T1) and P(T2) are assumed to be constant across trials (and potentially equal, if the hypothesis of an attentional split is verified); but the identity of the most and least attended locations is unknown on any given trial. Can we still get the probability estimates for the two events P(T1) and P(T2)?

The following equations hold:

$$P(\text{BOTH}) = P(\text{T1} \cap \text{T2}) = P(\text{T1}) \cdot P(\text{T2}), \quad (1)$$

$$\begin{aligned} P(\text{NONE}) &= P(\sim \text{T1} \cap \sim \text{T2}) \\ &= (1 - P(\text{T1})) \cdot (1 - P(\text{T2})) \\ &= 1 + P(\text{T1}) \cdot P(\text{T2}) - (P(\text{T1}) + P(\text{T2})). \end{aligned} \quad (2)$$

Probabilities P(BOTH) and P(NONE) can be estimated directly from the experimental data—unfortunately, the corresponding values were not reported in the study by Bichot et al. (1999), preventing a reevaluation of their conclusions.

Let $\Sigma = P(\text{T1}) + P(\text{T2})$ and $\Pi = P(\text{T1}) \cdot P(\text{T2})$. [Equations 1](#) and [2](#) can be rewritten as

$$\Pi = P(\text{BOTH}), \quad (3)$$

$$\Sigma = 1 + P(\text{BOTH}) - P(\text{NONE}). \quad (4)$$

Here we appeal to a general theorem of polynomial equations: for the equation $a_n x^n + a_{n-1} x^{n-1} + a_{n-2} x^{n-2} + \dots + a_0 = 0$, with $a_n \neq 0$, the sum of the roots is $-a_{n-1}/a_n$ and the product of the roots is a_0/a_n if n is even, and $-a_0/a_n$ if n is odd. From this theorem and [Equations 3](#) and [4](#), P(T1) and P(T2) are the solutions of the following second-degree equation:

$$X^2 - \Sigma \cdot X + \Pi = 0. \quad (5)$$

Solving [Equation 5](#) requires calculating its discriminant Δ , defined as

$$\Delta = \Sigma^2 - 4 \cdot \Pi. \quad (6)$$

If the discriminant Δ is zero, Equation 5 only has one solution and $P(T1) = P(T2)$: attention is equally allocated to the two targets. If Δ is positive, there are two distinct real solutions; the greatest solution is assigned to $P(T1)$ and the other solution to $P(T2)$: the attentional spotlight favors one of the two locations. Last, if Δ is negative, there are no real solutions to Equation 5—the solutions are complex numbers. If this were to happen with our data, it would likely be due to noise, as probabilities are real numbers: to obtain the solutions of the equation in this case, we artificially set Δ to zero; however, the proper (negative) value of Δ was retained in order to compare the distribution of discriminant values over subjects with the null hypothesis of $\Delta = 0$, as described below.

To determine whether there is an attentional split, we perform the estimation of $P(T1)$ and $P(T2)$ as explained above for each subject. The null hypothesis is that there is an equal split of attentional resources, i.e., that Δ is zero. Since we are dealing with experimental data, even if the null hypothesis is true we do not expect every subject's Δ to be exactly zero, but rather we expect individual Δ s to be distributed around zero. Our criterion for an attentional split thus consists in testing the mean of the distribution of Δ s against zero, using a one-sided t -test. If Δ is significantly positive ($p < 0.05$), the equal attentional split interpretation cannot hold any more.

It is important to note that subject-by-subject estimates will artificially separate the mean values of $P(T1)$ and $P(T2)$. Indeed, consider a situation in which $P(T1) = T + \varepsilon_1$ and $P(T2) = T + \varepsilon_2$, where T is the true probability of detecting a target and ε_1 and ε_2 are normally distributed error terms across subjects. The true means of $P(T1)$ and $P(T2)$ are the same, implying that attention is equally allocated to the two targets (in other words, $\Delta = 0$). For each subject, however, our method estimates two probability values and always assigns the greatest to $P(T1)$. The final mean estimates of $P(T1)$ and $P(T2)$ across subjects will thus artificially differ, even though they are drawn from distributions with the same mean. Therefore, we always refer to the distribution of Δ s first, before making any conclusions regarding $P(T1)$ and $P(T2)$: even when the mean values across subjects of $P(T1)$ and $P(T2)$ significantly differ, the hypothesis of an equal split of attention can only be rejected when Δ is significantly positive.

Finally, another way to look at the data is to pool all trials as if they came from a single subject and perform the estimation of $P(T1)$ and $P(T2)$ for this pooled data. Assuming that each subject's data is drawn from the same population distribution, we then obtain a better estimate of the underlying probabilities (i.e., smaller error terms ε_1 and ε_2); the estimates will be more reliable and less susceptible to the above-mentioned bias, providing a less misleading picture than the mean of individual estimates (with the obvious caveat that no estimate of inter-subject variability can be computed in this case). In the following, we analyze and report both the pooled data and the means of individual values across subjects.

Distractor locations

As described by Bichot et al. (1999), it is interesting to compare performance at distractor locations that are between the targets to performance at distractor locations that are outside the targets (“inside” and “outside” can only be defined when the two targets are separated by one or two distractors; when the two targets are separated by zero or three distractors, we put all distractors in the “outside” category); indeed if a single spotlight encompasses the two target locations and what is in the midst of them, then performance at distractor locations *between* targets should be greater than at distractor locations *outside* of targets.

Chance level

The average probability for a subject to report a given letter by chance on one trial depends on the number of letters they report. Say a subject reports three letters per trial on average, among the 20 possible letters. The number of three-letter reports comprising the letter of interest is $\binom{19}{2}$. The total number of three-letter reports is $\binom{20}{3}$. Hence, the probability for that subject to report a letter by chance is on average $\binom{19}{2} / \binom{20}{3} = 0.15$ (the same

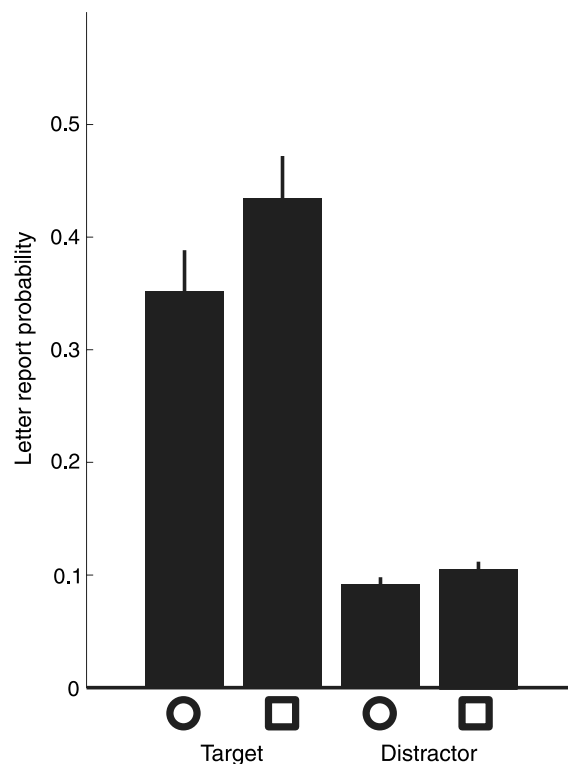


Figure 2. Letters in squares were more likely to be reported than letters in circles (data collapsed over SOAs).

calculation applied to the 7-SOA group, for which only 16 letter choices were given, would yield a chance level of $\binom{15}{2} / \binom{16}{3} = 0.1875$.

Results

Primary task (shape comparison)

All subjects performed well on the primary task (average correct: 86.7%, standard error of the mean 1.8%). As the SOA increased, performance on the task got slightly but significantly better (82.4% correct at 53.3 ms, 86.0% at 106.6 ms, 88.0% at 160 ms, and 90.6% at 213.3 ms; 1-way ANOVA for the effect of SOA, $F(3, 42) = 13.88$, $p < 10^{-5}$). Trials in which subjects responded incorrectly were discarded.

Secondary task (letter report)

We observed a stimulus-driven bias: letters presented inside squares were, on average, more likely to be reported than letters presented inside circles, as shown in Figure 2 (2-way ANOVA, $F(1, 14) = 74.06$, $p < 10^{-6}$ for [Circle/Square], $F(1, 14) = 59.65$, $p < 10^{-5}$ for [Target/Distractor], with a significant interaction $F(1, 14) = 34.04$, $p < 10^{-4}$ showing that the effect is more pronounced for targets than for distractors). This bottom-up advantage for squares could have lead to spurious conclusions regarding

the distribution of attention on trials in which the target shapes were different. We therefore only considered trials in which the target shapes were identical for subsequent analysis: that way, both target locations were expected to receive comparable amounts of exogenous attention.

First, we replicated the conditional probability results presented as the main evidence for a split attentional spotlight by Bichot et al. (1999), as shown in Figures 3 and 4. In Figure 3, we observed that, on average, the probability of reporting a letter at a target location was higher than at distractor locations, and this difference increased significantly with increasing SOA (2-way ANOVA, $F(1, 14) = 74.36$, $p < 10^{-6}$ for [target/distractor] and $F(3, 42) = 7.16$, $p < 10^{-3}$ for [SOA], with a significant interaction $F(3, 42) = 8.31$, $p < 10^{-3}$). Letters at distractor locations were reported significantly less often than they would have been by chance (2-way ANOVA, $F(1, 14) = 7.57$, $p < 0.05$ for [distractor/chance] and $F(3, 42) = 0.44$, $p = 0.73$ for [SOA], with a significant interaction $F(3, 42) = 3.37$, $p < 0.05$). This is due to the manner chance is calculated, depending on the average number of letters reported by each subject, and it shows that the primary task was effective in making subjects attend selectively and almost exclusively to the target locations. Distractor locations that were between target locations did not receive more attention than other distractor locations at any SOA (2-way ANOVA, $F(1,14) = 2.85$, $p = 0.11$ for [between/outside] and $F(3, 42) = 0.46$, $p = 0.71$ for [SOA], with no significant interaction $F(3, 42) = 0.69$, $p = 0.57$), thus arguing against the possibility of a single extended spotlight encompassing both target locations. In Figure 4, probabilities of letter report conditional on the

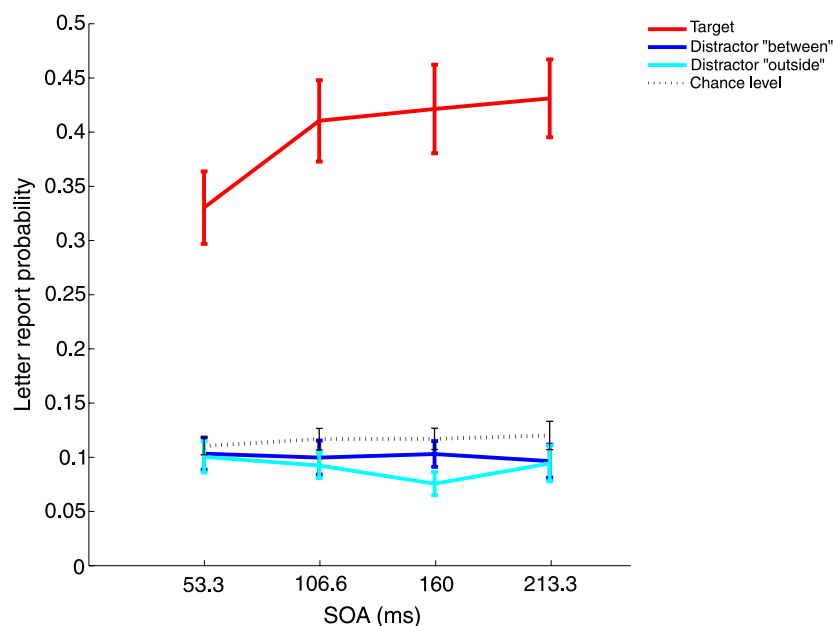


Figure 3. Probability of correct letter report as a function of SOA. Letters at target locations (red) are reported more often than letters at distractor locations (blue and cyan). Furthermore, performance is not better at distractor locations “between” (blue) than at distractor locations “outside” (cyan) of the two targets.

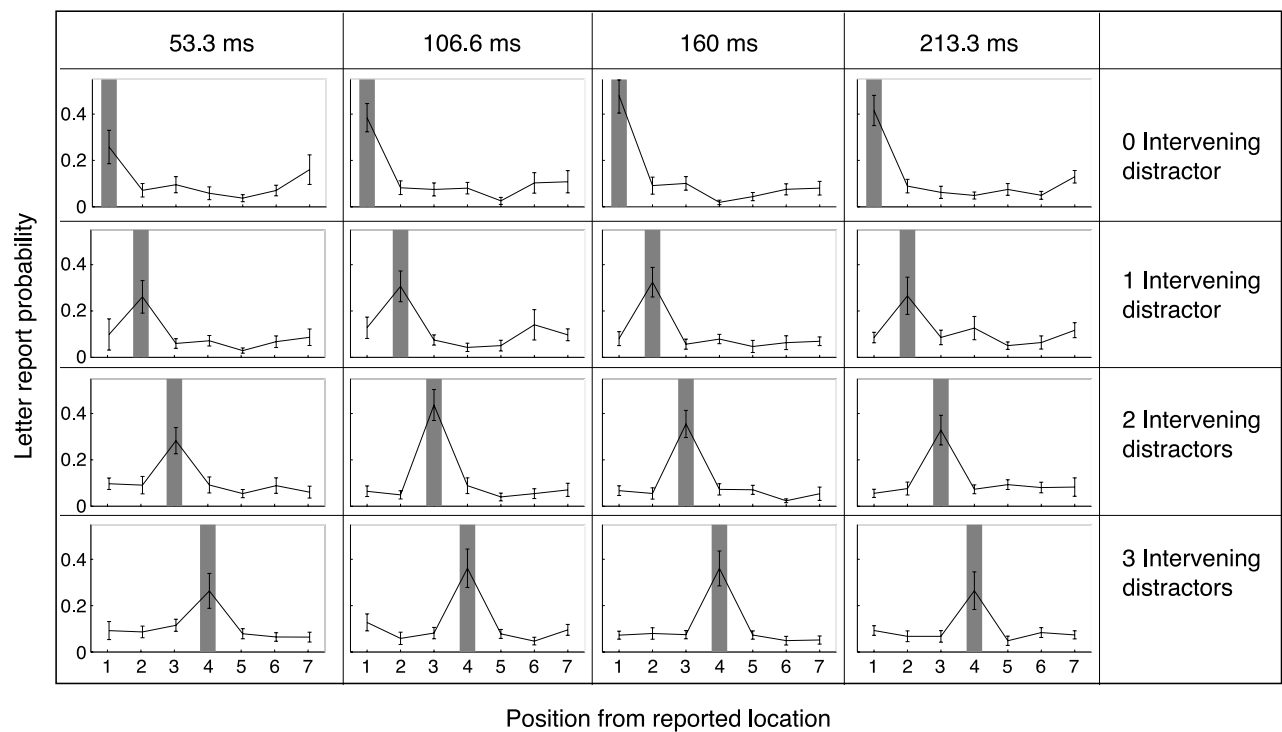


Figure 4. Conditional probabilities (computed as in Bichot et al., 1999). Each graph represents the probability of letter report as a function of the positional distance from a target letter that was correctly reported. Position 1 is the shape right next to the correctly reported target location. The shaded gray bar indicates the location of the second target. Positions are counted around the circle so that the second target always falls within positions 1 to 4.

report of one target are plotted. The conditional probability of reporting the other target was significantly higher than the conditional probability of reporting a distractor, and this difference significantly increased with SOA, which reflects the previous observation that target letter report performance increases with SOA (see Figure 3; 3-way ANOVA, $F(1, 14) = 22.99$, $p < 10^{-3}$ for [target/distractor], $F(3, 42) = 4.12$, $p < 0.05$ for [SOA], and $F(3, 42) = 3.46$, $p < 0.05$ for [target separation], with a significant interaction between [target/distractor] and [SOA] $F(3, 42) = 4.63$, $p < 0.01$). Likewise, in the cases of one or two intervening distractors, the conditional probability of report for distractors between targets is not significantly different from the conditional probability of report for distractors outside targets at any SOA or any target separation (3-way ANOVA, $F(1, 14) = 0.752$, $p = 0.40$ for [distractor between/distractor outside], $F(3, 42) = 0.57$, $p = 0.64$ for [SOA], and $F(1, 14) = 1.98$, $p = 0.18$ for [target separation], with no significant interactions). At first sight, our data are thus compatible with the data that Bichot et al. (1999) based their conclusions on.

We then analyzed the results with our improved calculation procedure, as described in the Methods section (Figure 5). We estimated the probabilities P(BOTH) and P(NONE) for each subject in turn, which allowed us to solve a simple second-degree equation and estimate P(T1) and P(T2), the probabilities of correct letter report at the

most and least attended target locations, respectively. Because potential measurement errors across individual subjects do not cancel out but instead add up in this analysis (due to our systematically assigning the largest of the 2 computed probabilities to P(T1), as explained in detail in the Methods section), we also performed the same analysis on pooled data, using all trials from all subjects as though they came from a single subject. This pooled calculation, illustrated by thick lines in Figure 5, will be less prone to measurement error. Only trials in which there was at least one intervening distractor were considered; indeed, when the target locations are adjacent, the spotlight need not be divided to illuminate both target locations simultaneously.

Critically, the spatial distribution of attention between the two target locations was found to depend on SOA (2-way ANOVA, $F(3, 42) = 9.50$, $p < 10^{-4}$ for [SOA], $F(1, 14) = 50.181$, $p < 10^{-5}$ for [T1/T2] with a significant interaction $F(3, 42) = 3.95$, $p < 0.05$). This result goes together with a significant effect of SOA on the discriminant (1-way ANOVA, $F(3, 42) = 3.25$, $p < 0.05$). A post-hoc analysis using Tukey's Honestly Significant Differences test shows that the discriminant at the longest SOA (213.3 ms) is significantly higher than at the shortest SOAs (53.3 ms and 106.6 ms). We can already conclude that the bias of attention for one target location over the other increases with time. Further tests show that for

SOAs at or below 106.6 ms, the two target locations apparently received comparable amounts of attention: the discriminants across subjects did not statistically differ from zero (one sided t -test, $t(14) = 1.27$, $p = 0.11$ at 53.3 ms and $t(14) = 0.93$, $p = 0.18$ at 106.6 ms); the discriminant estimated from the pooled data was close to zero (-0.01 at 53.3 ms and -0.01 at 106.6 ms), providing graphical confirmation. Note that this result is consistent with the conclusions of Bichot et al. (1999), who investigated a single SOA of 105 ms. For SOAs of 160 ms or greater, one of the target locations was found to win the attentional competition, receiving more attention as the SOA

increased: the discriminants across subjects were statistically larger than zero (one sided t -test, $t(14) = 3.54$, $p < 0.01$ at 160 ms and $t(14) = 3.36$, $p < 0.01$ at 213.3 ms) and the discriminant estimated from the pooled data was larger than zero (0.01 at 160 ms and 0.04 at 213.3 ms). These results are summarized in Figure 5.

Discussion

In this experiment, two target locations were cued with odd-color shapes and were behaviorally relevant for the subject's primary task (shape comparison). Letters were briefly presented inside the shapes, and we estimated the probabilities of correct letter report at the most and least attended target locations as a proxy for the amount of spatial attention that each of these locations received. It turned out that for short stimulus onset asynchronies (the time between the presentation of the cues and the appearance of the letters inside them) the probabilities of correct letter report at the two target locations were comparable; that is, resources appeared to be equally allocated to the two concurrent target locations. However, this early state evolved into the selection of one target location over the other when the stimulus onset asynchrony increased: one of the spotlight's initial two beams died out as the other beam gradually used more resources. Our results thus point to two successive modes for the deployment of attention in space: an early, transient mode in which multiple locations can be attended and a later, maybe more sustained mode in which attention needs to focus on a single location at a time.

Given our procedure and instructions, it is difficult to determine whether the odd-color feature cues acted in an exogenous (bottom-up) or endogenous (top-down) manner. Some evidence to this effect can be derived from a pilot study (as yet unpublished) in which 8 participants performed the experiment without a primary shape

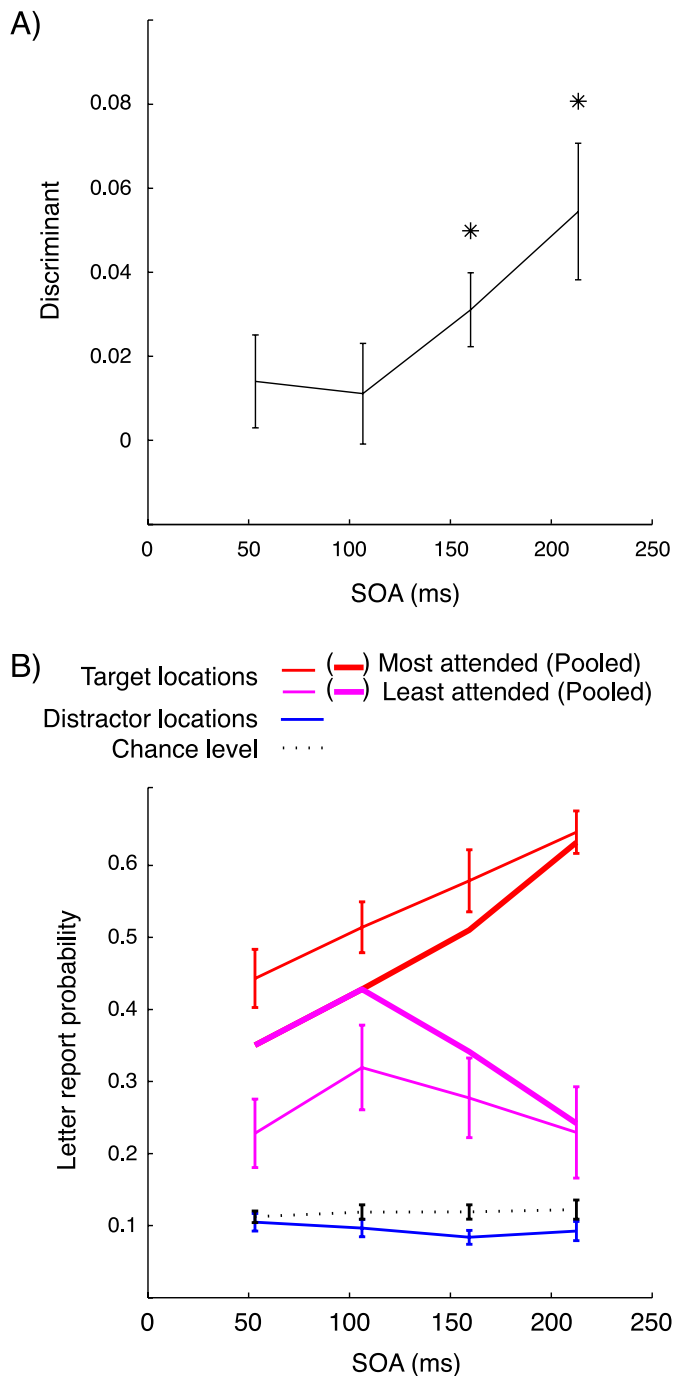


Figure 5. Deployment of the spotlight of attention as a function of SOA. (A) The average discriminant across subjects is not significantly different from zero for SOAs shorter or equal to 106.6 ms, whereas it is significantly above zero for SOAs longer or equal to 160 ms. This implies that, at least for the two largest SOAs, the conclusion that the 2 targets receive equal amounts of attention is not warranted. (B) The probability of report at the most attended location keeps increasing with increasing SOAs, whereas the probability of report at the least attended location starts decreasing: attention focuses most of its resources on one target at longer SOAs. The pooled (thick lines) and individual data (thin lines), respectively, provide a more conservative and a more liberal estimate of the "split attention" hypothesis. In both cases, however, this hypothesis is found not to hold for SOAs larger than 106 ms.

comparison task; preliminary analysis revealed that the two odd-color shapes in this case were treated no differently from the distractors, indicating that our present findings may be limited to behaviorally relevant targets.

One may argue that the observed selection of one single location at SOAs between 107 ms and 160 ms is an artifact of saccades that subjects made to one of the targets, despite the clear instructions to not move their eyes. We did not record eye movements so we do not have definite evidence to reject this argument. Average saccadic latencies between 180 and 250 ms have been reported in humans in experimental conditions similar to ours, i.e., with no offset of the fixation cross prior to the saccade (McPeck, Maljkovic, & Nakayama, 1999; Song & Nakayama, 2007; Yang, Bucci, & Kapoula, 2002). The duration of an ~ 5 degree amplitude saccade is in the range of 30–45 ms (Carpenter, 1988). It would thus take on average 210 to 300 ms for subjects to fixate one of the targets if they were instructed to do so. We argue that the observed selection of a single location between 107 ms and 160 ms occurs too early to be accounted for by the execution of an eye movement. It is reasonable to suppose, however, that the oculomotor system may have been *planning* a saccade. Indeed, our results are a natural prediction of a certain class of computational models of attention (Hamker, 2004) in which the planning of saccadic eye movements guides attentional selection, in line with the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltà, 1987). In this model of saccadic decision making and attention, the frontoparietal network receives the current output of a “refined” distributed saliency map (Hamker, 2006) and selects the unique location of an eye movement by a competition over time. Activity from this frontoparietal network is fed back continuously to extrastriate visual areas. Thus, the SOA determines the state of this competition at the time the letters are flashed, and ultimately the distribution of attention at different locations. While the amount of motor in the premotor theory has been a subject of intense debate (Chambers & Mattingley, 2005; Hamker, 2005; Juan et al., 2008; Juan, Shorter-Jacobi, & Schall, 2004; Thompson, Biscoe, & Sato, 2005) our results argue for feedback signals from cells in oculomotor areas that have knowledge about the motor plan.

In light of our previous distinction between transient and sustained attention modes, it is likely that some of the evidence reported in favor of a split of the spotlight only addressed the transient attention mode (Baldauf & Deubel, 2008; Bichot et al., 1999; Carlson et al., 2007; Godijn & Theeuwes, 2003; Kramer & Hahn, 1995). Other reports that clearly pertained to the sustained attention mode (Awh & Pashler, 2000; Gobell et al., 2004; Kraft et al., 2005; McMains & Somers, 2004, 2005; Müller et al., 2003; Pylyshyn & Storm, 1988) may not have possessed the temporal resolution necessary to distinguish between multiple spotlights and a unique, rapidly switching one. In particular, the main argument to discard the switching

spotlight model in the SSVEP study by Müller et al. (2003) and in the fMRI studies by McMains and Somers (2004, 2005) is that of limited stimulus presentation times (around 170–180 ms). But in a recent study involving sustained monitoring of multiple locations, VanRullen et al. (2007) reported evidence for an undivided spotlight in constant periodic motion, sampling its multiple targets at a rate of seven items per second. Of course, there might be circumstances outside of those tested in the present study in which a split attentional spotlight may be sustained. In any case however, our results suggest that the seemingly disparate literature on attentional allocation to multiple targets could be reconciled by considering time (transient or sustained attention mode) as a critical factor.

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