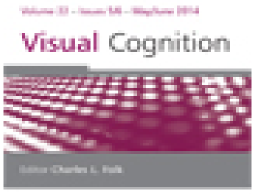

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Splitting the attentional spotlight? Evidence from attentional capture by successive events*

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ABSTRACT
Must attention be disengaged from a location before it can be moved to another? We addressed this question in four experiments. Participants searched for a target defined by its colour. The search display followed either one or two successive singleton cues that were expected to capture attention because they were in the target colour. We found a spatial benefit at the location of the first cue even though attention had been shifted to the location of the second cue. However, this benefit was smaller than when the second cue had been absent. These findings suggest that attention can be directed to a new location before it is entirely disengaged from its previous locus. We tested and rejected alternative interpretations, according to which this residual spatial effect resulted from occasional failures of attentional capture by the second cue, or from variability of the speed at which attention was shifted from one cue to the other. Taken together, our findings suggest that shifting attention from one location to another results in two simultaneous foci of attention for at least 300 ms. We discuss the possibility that the residual spatial benefits observed here may reflect pre-attentive tagging rather than parallel allocation of a limited resource to two separate locations.

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Spotlight; split attention; spatial selection; attentional capture; spatial cueing; contingent capture

Over the course of just a few seconds, we typically shift our attention many times. For instance, imagine that while you drive your car, a truck springs into your field of view and a split second later, your cellphone's screen brightens to signal that you received a new message. Your attention is likely to automatically shift to the first and second events in rapid succession. In this situation, does allocating your attention to your cellphone's screen entail that it was entirely removed from the potentially dangerous truck or can both locations benefit from your attention simultaneously?

This question is related to two broader issues in attention research, which have generated a steady stream of investigations ever since Posner, Snyder, and Davidson (1980) introduced the metaphor of attention as a spotlight. One concerns whether the focus of attention is unitary or can be split among non-contiguous regions of the visual field. According to serial models, attention is indivisible and has to first be disengaged from a location before it can be moved to another, whereas parallel models suggest that attention can be allocated to several locations or objects simultaneously (for reviews, see Cave, Bush, & Taylor, 2010; Jans, Peters, & De Weerd, 2010). The other issue concerns the speed at which attention can be shifted from one location to another, with estimates varying considerably, from very fast shifts (50 ms and lower, e.g., Eimer & Grubert, 2014; Treisman, 1988; Wolfe, 2007), to moderately fast (80–150 ms, e.g., Grubert & Eimer, 2016; Woodman & Luck, 1999) and slow shifts (200 ms and more, e.g., Duncan, Ward, & Shapiro, 1994; Moore, Egeth, Berglan, & Luck, 1996).

The studies exploring these questions do not speak directly to the issue that is the focus of the present study: can shifting attention from one location to another result in two simultaneous foci of attention or is the first focus extinguished before the next is lit up? On the one hand, a desired feature of studies investigating whether attention can be divided between two non-contiguous regions is that they should exclude the possibility that attention was rapidly shifted between the critical locations (e.g.,

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*The data that support the findings of this study are openly available in Figshare at https://figshare.com/articles/Splitting_the_spotlight_Evidence_from_attentional_capture_by_successive_events/7855574.

Jans et al., 2010). Thus, these cannot offer any insights into whether residual benefits linger at the previous focus of attention after attention is shifted to another. On the other hand, unless attentional shifts are found to be so fast as to make it improbable that attention was entirely disengaged from its previous locus before it was shifted (e.g., Eimer & Grubert, 2014, who reported attentional shifts of 10 ms), how fast attention can be shifted and whether it must be fully disengaged before it is reallocated are orthogonal questions.

Indirect evidence pertaining to our research question comes from electrophysiological studies (Busse, Katzner, & Treue, 2008; Eimer & Grubert, 2014; Grubert & Eimer, 2015; 2016; Khayat, Spekreijse, & Roelfsema, 2006) and generally supports the notion that attention can be maintained at two successive locations.

In Khayat et al.'s (2006) study, monkeys had to select a target curve and ignore a distractor curve, while activity from single neurons in their primary visual cortex was recorded. Some trials required a shift of attention, because the target and distractor curves were switched during the course of the trial. When the monkeys had to shift their attention because of the curve switch, responses to the newly attended curve were strongly enhanced 144 ms after the trigger to shift attention, whereas responses to the curve from which attention was removed were suppressed only 210 ms after this trigger. The 60 ms delay between enhancement at the new location and suppression at the old location led the authors to conclude that attention can be rapidly allocated to a new object before it disengages from the previously attended one. In a similar study combining exogenous and endogenous shifts of attention and recording single cell activity in MT, Busse et al. (2008) reported that allocation of attention to a target occurred about 120 ms earlier than withdrawal of attention from a previously attended object.

Eimer and Grubert (2014, Experiment 2) used the N2pc component of the event-related potential (ERP), a negative-going deflection of the EEG waveform with a maximum over visual (posterior) areas contralateral to the location of an attended stimulus (e.g., Eimer, 1996; Luck & Hillyard, 1994) as an ERP marker of the locus of visual attention. On each trial, two brief displays were presented sequentially, with stimulus asynchronies (SOAs) of 10, 20, 50 or100 ms in different blocks. Each display contained a colour-defined target in one location and a distractor in the opposite location. Participants had to determine whether the two successive targets belonged to the same or different categories. One stimulus pair always appeared on the vertical meridian (above and below fixation), and the other stimulus pair appeared on the horizontal meridian (left or right to the fixation). Because the N2pc is measured by comparing ERP waveforms associated with attended objects in the left versus right visual fields, no N2pc is elicited by targets appearing on the vertical meridian. Thus, allocation of spatial attention to one target (on the horizontal meridian) could be measured independently of the allocation of spatial attention to the other target (on the vertical meridian). The results showed that with SOAs as short as 10 ms an N2pc of equal size was elicited by horizontal targets in the first and second displays, with an onset latency difference closely matching the onset difference between the two targets. Moreover, the N2pc components were identical in size for the 10-ms and 100-ms SOAs, ruling out the possibility that when two targets appear almost simultaneously, attention is directed randomly to only one of them. The authors concluded that when two visual objects appear in rapid succession, attention can be allocated to the second target and simultaneously remain focused on the first.

In a follow-up study, Grubert and Eimer (2016) replicated the finding that two successive N2pc components can be elicited by successive targets when sequential focusing of attention is required by the task. They also reported a corollary finding showing that *after* the N2pc component indexing attentional allocation to the second target, there was a late sustained posterior negativity (held to reflect the spatially selective activation of target representations in visual working memory, e.g., Mazza, Turatto, Umiltà, & Eimer, 2007) contralateral to the first target. The authors interpreted this finding as providing further evidence that attention is not fully disengaged from its first locus before it is shifted to a new location.

Taken together, the findings of the foregoing studies are highly suggestive of the notion that allocating attention to a new location does not require disengagement from its previous locus. However, the evidence they provide is only indirect, as the time course and amplitude of neural activity in brain areas such as V1, MT and the parietal regions in which the N2pc component is thought to originate, do not necessarily provide a direct window into the time course of attentional allocation (e.g., Bisley & Goldberg, 2003). It is therefore important to test these conclusions using behavioural data. This was the objective of the experiments reported here.

We used a variant of the spatial cueing paradigm pioneered by Folk and Remington (1998). In the feature-search version of the typical paradigm, participants are required to search for a target defined by its known colour (e.g., red) among heterogeneously coloured distractors, and to report its shape. Shortly prior to the search display, a salient uninformative cue, for instance, a colour singleton (e.g., a red object among uniformly grey objects) appears in one of the possible target locations. An attentional shift to (or capture by) the cue is measured as the performance benefit on trials in which the target happens to appear at the cued location relative to trials in which it appeared elsewhere (henceforth, same-location benefit or location effect). A flurry of findings has shown that when the cue shares the target-defining feature (e.g., the target and cue are red), it reliably captures attention (Ansorge, Horstmann, & Carbone, 2005; Carmel & Lamy, 2014; Eimer & Kiss, 2008; Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Lamy, Alon, Carmel, & Shalev, 2015; Zivony, Allon, Luria, & Lamy, 2018).

Here, in order to trigger two successive shifts of attention, two successive target-colour cues (henceforth, C1 and C2), instead of just one, appeared prior to the search display. The design included a baseline condition in which the second cue was omitted (henceforth, C2-absent trials). We reasoned that if allocating attention to a new location does not require disengagement from its previous locus, same-location benefits should be observed at the locations of both the second cue (henceforth, C2-location effect) and the first cue (henceforth, C1-location effect).

We expected a significant C2-location effect because previous studies (e.g., Chen & Mordkoff, 2007; Lamy, 2005; Lamy, Leber, & Egeth, 2004) reported attentional capture by target-colour cues with cue-target SOAs shorter than the shortest SOAs used in the present study between the second cue and the target (100 ms). We also expected a significant C1-location effect when the second cue was absent, because previous studies (e.g., Carmel & Lamy, 2014; Lamy et al., 2004; Remington, Folk, & Mclean, 2001) reported attentional capture by target-colour cues with cue-target SOAs as long as or longer than the longest SOAs used in the present study between the first cue and the target (400 ms).

The question of main interest here was whether attention would be deallocated from the locus at which it was initially captured before it was re-shifted to a different location. In other words, we asked whether a location effect would still be observed at the location of the first cue after attention had been reallocated to the location of the second cue. If attention is entirely deallocated from the location of the first cue before it is shifted to the location of the second cue, then the C1-location effect should be eliminated when the second cue is present relative to when it is absent. This outcome would support serial models of attention (e.g., Posner & Cohen, 1984). Conversely, if attention can be allocated independently to successive stimuli at no cost, the C1-location effect should be unaffected by the presence of the second cue, in line with parallel models of attention (e.g., Eimer & Grubert, 2014).

The interpretation of an intermediary pattern of results is less straightforward. A reduced yet significant C1-location effect might indicate that within a certain time window, spatial attention can simultaneously accrue to two separate locations. However, two alternative accounts that are compatible with strictly serial models of attention are possible. One is that the residual benefit at the location of the first cue may emanate from a portion of trials in which the second cue failed to capture attention altogether. The other is that the time necessary to move attention from one location to the other may vary across participants or trials, such that simultaneous benefits at the locations of the two cues may simply reflect that while attention is still focused at the location of the first cue for some participants (or trials), it is already shifted to the location of the second cue for the remaining participants (or trials). As will become clear below, we took several steps to disentangle these possibilities.

Statistical analyses

The following data exclusion procedures and analyses were conducted in all experiments. Error trials were excluded from all RT analyses. Reaction time outliers, defined as any trial with an RT deviating from the median RT of its cell by more than 3 median absolute deviations (Leys, Ley, Klein, Bernard, & Licata, 2013), were also excluded. Because it was important to disentangle the effects of the first and second cues, trials in which C1 and C2 shared the same location (12.5% of all trials) were excluded from the main analyses. However, for completeness, the data from these trials are examined in separate analyses.

We first examined the effect of the second cue on responses to the target, by analysing the *C2-location effect*, that is, by comparing performance when the target appeared at the same vs. different location relative to the second cue. In this analysis, we did not include trials in which the first cue had appeared at the same location as the target because such trials might contaminate the C2-location effect by speeding average RTs on different C2-location trials.

We then examined the effect of the first cue on responses to the target, by analysing the *C1-location effect,* that is, by comparing performance when the target appeared at the same vs. different location relative to the first cue. In this analysis, we did not include trials in which the second cue, when present, appeared at the same location as the target because such trials would contaminate the C1-location effect by speeding average RTs on different C1-location trials. A similar subset of trials was randomly excluded from C2-absent trials in order to keep the same number of C2-present and C2-absent trials in all analyses. Crucially, we compared the C1-location effect when the second cue was present relative to when it was absent. Finally, we examined whether the C1-location effect remained significant when the second cue was present, in a planned comparison.

In a last analysis, the C1-location effect was examined when the second cue was absent relative to when it was present and appeared at the same location as the first cue (which are the trials that were excluded from the preceding analyses). As all different C1-C2 location trials were excluded from that analysis, a similar subset of trials was randomly excluded from C2-absent trials in order to keep the same number of C2-present and C2-absent trials.

Experiment 1

Method

Sample size selection

We calculated the sample size required to detect a significant spatial cueing (or location) benefit with a relevant-colour cue, based on the results reported by Carmel and Lamy (2014, Experiment 2). We used G*Power (Faul, Erdfelder, Buchner, & Lang, 2013) with an alpha of .05, power of .80, and the effect size reported by Carmel and Lamy ($\eta_p^2 = .52$). We found the minimum required sample size to be 6 participants. Therefore, we were confident that using 16 participants would provide us with enough power to detect a spatial cueing effect.

Participants

Participants were 16 Tel Aviv University undergraduate students (14 females, mean age = 23.3, *SD* = 2.35), who participated in the experiment for course credit. All reported having normal or corrected-to-normal vision acuity and normal colour vision.

Apparatus

The displays were presented on a 23-inch LED monitor, using the 1920X1280 resolutions graphics mode, in a dimly lit room. A chinrest was used to set the viewing distance at 50 cm from the monitor.

Stimuli

Each trial included three types of displays: a fixation, a cue, and a target display. The fixation display consisted of a grey 0.2°×0.2° plus sign in the centre of the screen against a black background and surrounded by four 1-pixel-thick grey circles (1° in radius and distant from fixation by 2.8°), each containing the letter “H” in its centre. The cue display was identical to the fixation display when the cue was absent. When the cue was present, the cue display differed from the fixation display only in the fact that the four circles were 2-instead of 1-pixel thick and one circle (the cue) was red. This cueing procedure was used in order to ensure that a change occurred in all locations (and not only at the location of the cue, see Carmel & Lamy, 2014). The target display was similar to the fixation display, except that the grey H letters were replaced with a red, a blue, a green and a yellow T letters, two rotated by 90 degrees to the right and two to the left (the superimposition of which corresponded exactly to the H stimuli used in the fixation display). The target was the red T. Thus, the cues and target were of the same colour. All letters subtended 0.8° x 0.6°.

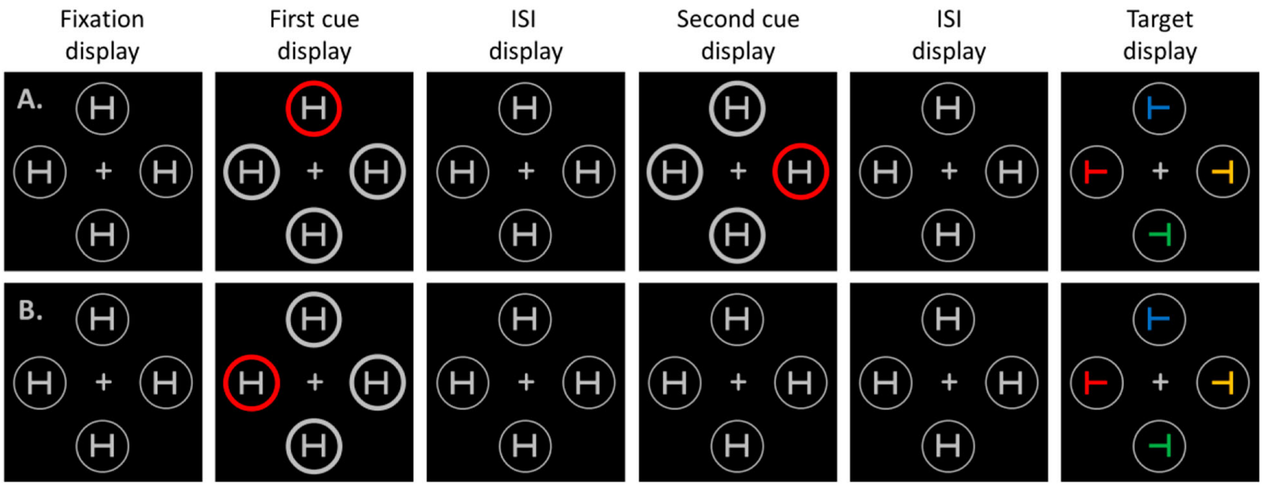

Figure 1. Sequence of events in Experiment 1. The target was the red T and the red circles were the cues. The locations of the cues and target were uncorrelated. *Upper panel*. Sample C2-present trial, in which both the first and second cues appeared at different locations relative to the target. *Lower panel*. Sample C2-absent trial in which the first cue appeared at the same location as the target. Note that the time interval between the first cue and the target was identical when the second cue was present and when it was absent.

Procedure

The sequence of events is illustrated in Figure 1. Each trial began with the fixation display, which remained on the screen for 500 ms. Then, a first cue display, the fixation display, a second cue display and a second fixation display were presented sequentially, for 50 ms each. Note that the time interval between the first cue and the target was identical when the second cue was present and when it was absent (see Figure 1). Finally, the target display appeared until response or for 1500 ms, whichever came first. On each trial, participants made a speeded response to the orientation of the red "T". They were instructed to use the computer's numerical keypad and to press "3" if the target T was oriented to the right and "1" if it was oriented to the left. An incorrect response was followed by a 500-ms feedback beep. If no response was made within 1,500 ms, an error was scored. Participants were instructed to respond as quickly and accurately as possible and to maintain their gaze on the plus sign.

Design

The first cue was present on all trials and the second cue was present on 50% of the trials (C2-present condition) and absent on the remaining trials (C2-absent condition). The positions of the first cue, the second cue (when present) and the target were selected randomly on each trial and were therefore uncorrelated. All conditions were randomly mixed. Each session lasted for 30 min. It began with a 20-trial practice block, followed by 512 trials divided into 8 blocks. The participants were allowed a self-paced rest after each block.

Results

Error trials (4.9%) as well as RT outliers (1.72% of all correct trials) were excluded. The mean location effects on RTs and accuracy data are presented in Figure 2. Mean RTs and accuracy scores are presented in Table 1.

Location effect for the second cue

We conducted an analysis of variance (ANOVA) on C2-present trials with C2 location (same vs. different relative to the target) as a within-subject factor. Same-location trials were significantly faster and more accurate than different-location trials, $F(1, 15) = 104.2$, $p < .0001$, $\eta_p^2 = .87$, $F(1, 15) = 7.14$, $p = .02$, $\eta_p^2 = .32$, respectively.

Location effect for the first cue

We conducted an ANOVA with C1 location (same vs. different relative to the target) and C2 presence (present vs. absent) as within-subject factors.

Reaction times. Both the main effects of C1 location and C2 presence were significant, indicating that responses were faster when the target appeared at

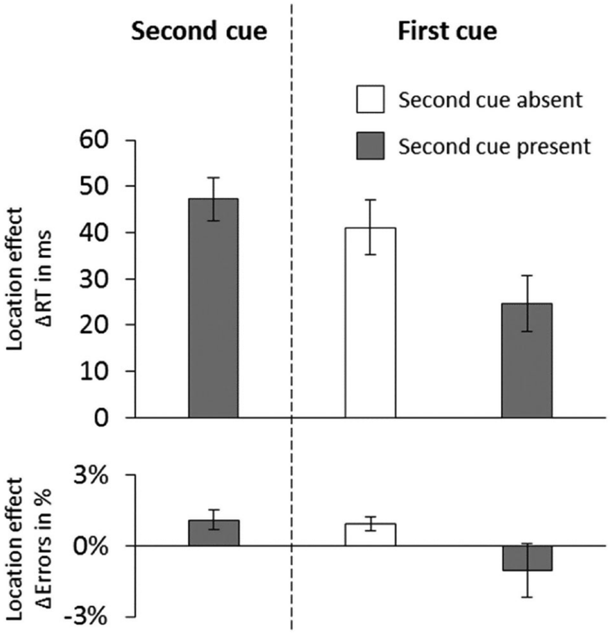

Figure 2. Mean location effect (different location minus same location) on reaction times (upper panel) and on error rates (lower panel) in Experiment 1. The left bars depict the location effect relative to the second cue. The middle and right bars depict the location effect relative to the first cue when the second cue was absent and present, respectively. Error bars denote within-subject standard errors (Morey, 2008).

the same location as C1 than at a different location, $F(1, 15) = 37.68$, $p = .0001$, $\eta_p^2 = .72$ and when C2 was absent than when it was present, $F(1, 15) = 58.98$, $p < .0001$, $\eta_p^2 = .80$. The interaction between the two factors was significant, $F(1, 15) = 9.89$, $p = .007$, $\eta_p^2 = .40$, indicating that the C1-location effect was larger when C2 was absent than when it was present. Planned comparisons revealed that this effect was significant both when C2 was absent, $F(1, 15) = 47.61$, $p < .0001$, $\eta_p^2 = .76$ and when it was present, $F(1, 15) = 17.14$, $p = .0009$, $\eta_p^2 = .53$.

Accuracy. There was no significant main effect or interaction, $F < 1$, $F(1, 15) = 2.17$, $p = .16$, $\eta_p^2 = .13$ and $F(1, 15) = 2.30$, $p = .15$, $\eta_p^2 = .13$, for the main effect of C1 location, of C2 presence, and the interaction between them, respectively. Planned comparisons showed that the C1 location effect was significant when C2 was absent, $F(1, 15) = 9.06$, $p = .009$, $\eta_p^2 = .38$, but not when C2 was present, $F < 1$.

Location effect for the first cue (when it shared the second cue's location)

We conducted an ANOVA with C1 location (same vs. different relative to the target) and C2 presence (present vs. absent) as within-subject factors, on trials in which the second cue, when present, shared the first cue's location.

Reaction times. The main effect of C1 location was significant, indicating that responses were faster when the target appeared at the same location as C1 than at a different location, $F(1, 15) = 63.04$ $p = .0001$, $\eta_p^2 = .77$. Neither the main effect of C2 presence nor the interaction between the two factors reached significance, $F(1, 15) = 3.00$, $p = .10$, $\eta_p^2 = .17$ and $F(1, 15) = 3.03$, $p = .10$, $\eta_p^2 = .17$, respectively. However, further examination revealed that the C1-location effect tended to be larger when C2 was present than when it was absent, 56 ms vs. 39 ms, respectively.

Accuracy. There was no hint of a speed accuracy trade-off. The main effect of C1 location was significant, $F(1, 15) = 9.30$, $p = .008$, $\eta_p^2 = .38$ and the main effect of C2 presence approached significance, $F(1, 15) = 3.95$, $p = .07$, $\eta_p^2 = .21$. The interaction between the two factors was not significant, $F < 1$.

Discussion

In Experiment 1, as expected, cues sharing the target colour captured attention: there was a spatial benefit at the location of the first cue when the second cue was absent, and at the location of the second cue when this cue was present. The central finding was that the spatial benefit at the location of the first cue

Table 1. Mean reaction times (in milliseconds) and accuracy rates in Experiment 1 when the target appeared at the same vs. different location relative to the second cue (upper row) and relative to the first cue when the second cue was absent vs. present (lower two rows). Within-subject standard errors (Morey, 2008) are presented in parentheses.

		Reaction times (in ms)		Accuracy rates	
Cue	Second-cue condition	Same location	Different location	Same location	Different location
Second cue	Present	536 (2.6)	583 (2.8)	99.7% (0.3%)	98.6% (0.3%)
First cue	Absent	526 (3.7)	567 (3.2)	99.5% (0.3%)	98.6% (0.3%)
	Present	558 (3.8)	583 (2.8)	97.6% (0.9%)	98.6% (0.3%)

was significant even after attention had been redirected to the second cue, but this effect was reduced to about a half relative to when the second cue was absent and no reallocation of attention had therefore occurred.

As explained in the introduction, these results lend themselves to different interpretations. In the next experiment, we specifically tested the possibility that the residual spatial benefit may stem from a proportion of trials in which the second cue failed to capture attention. According to this scenario, this proportion would have to be roughly half of the trials, since the size of the residual C1-location effect when the second cue was present was about half of the effect when the second cue was present.

Experiment 2

In Experiment 2, we manipulated the salience of the second cue in order to increase the probability that it should capture attention. We reasoned that if the residual benefit at the location of the first cue observed in Experiment 1 when the second cue was present emanated from trials in which the second cue failed to capture attention, there should ample room for increasing such capture since it would have occurred only on half of the trials. Accordingly, this residual effect should be smaller or even disappear if the second cue is made more salient, because cues sharing the target defining feature are more likely to capture attention the more salient they are (e.g., Lamy et al., 2004).

This experiment was similar to Experiment 1, except for the following changes. We added a condition in which the second cue was made thicker, thereby creating two conditions of cue salience (a 2-pixel thick cue and a more salient 5-pixel thick cue), instead of just one (see Lamy (2005) for a similar manipulation). We also increased the target's thickness: as cues are more likely to capture attention the more similar they are to the target (e.g., Folk et al., 1992), it was important to keep similarity between the target and the second cue maximal when this cue was salient. If the second cue indeed failed to capture attention on a substantial proportion of the trials in Experiment 1, the C2-location effect in the present experiment should be larger in the high- than in the low-salience C2 condition. To the extent that it is, finding that the residual C1-location effect is reduced or eliminated in the former relative to the latter condition would indicate that attention is entirely disengaged from its previous locus before it is shifted to a new location. Such a result would support serial models of attention.

Method

Sample size selection

On the basis of the results of the previous experiment, we calculated the sample size required to detect a significant C1-location effect when C2 is present. We conducted this analysis with G*Power (Faul et al., 2013), using an alpha of .05, power of .80, the effect size reported in Experiment 1 ($\eta_p^2 = .53$), and the correlation between observations ($r = .83$). We found the required minimum sample size to be 3 participants. Therefore, in Experiments 2–4, we used the same number of participants as in Experiment 1 (16 subjects).

Participants

Participants were 16 (11 females, mean age = 23.5, *SD* = 2.28) Tel Aviv University undergraduate students who participated in the experiment for pay (10$). All reported having normal or corrected-to-normal vision acuity and normal colour vision.

Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 1 with four exceptions. First, we added a high-salience C2 condition, in which the circles in the second-cue display were thicker (the four circles were 7- instead of 2-pixel thick). Thus, the design included three C2 conditions: C2 absent, C2 non-salient and C2 salient. These were equiprobable and randomly mixed. Second, the letters in the target display were also thicker (5- instead of 2- pixel thick). Third, to generalise our data beyond the colour red, eight participants searched for a red target (and both cues were also red) and eight participants searched for a green target (and both cues were also green). Finally, the number of trials was increased: the experiment began with a 20-trial practice block followed by 960 experimental trials, divided into 12 blocks and lasted for 45 min.

Results

In all RT analyses, error trials (2.5% of all trials) as well as RT outliers (3.56%) were excluded. The mean

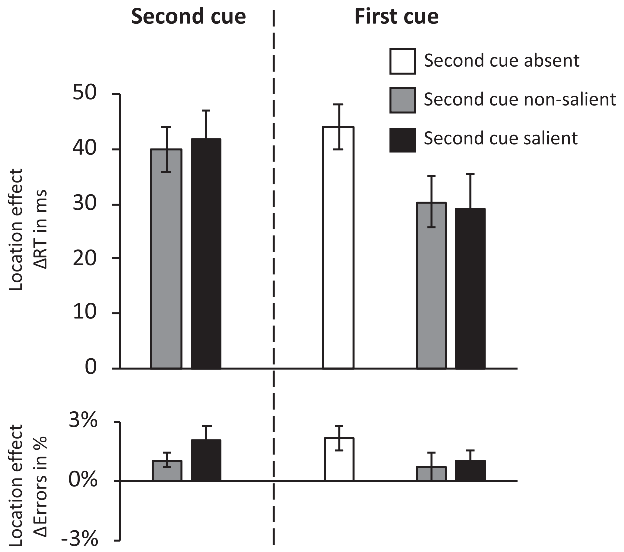

Figure 3. Mean location effect (different location minus same location) on reaction times (upper panel) and on error rates (lower panel) in Experiment 2, relative to the second cue (left) and relative to the first cue (right), as a function of whether the second cue was absent, non-salient or salient. Error bars denote within-subject standard errors (Morey, 2008).

location effects on RTs and accuracy data are presented in Figure 3. Mean RTs and accuracy scores are presented in Table 2.

Location effect for the second cue

We conducted an ANOVA on C2-present trials with C2-target location (same vs. different) and C2 salience (salient vs. non-salient) as within-subject factors.

Reaction times

The main effect of C2 location was significant, $F(1, 15) = 108.4$, $p < .0001$, $\eta_p^2 = .88$, with faster RTs on same- than on different-location trials. Neither the main effect of C2 salience nor the interaction between the two factors was significant, $F(1, 15) = 2.15$, $p = .16$, $\eta_p^2 = .13$ and $F < 1$, respectively.

Accuracy

The main effect of C2 location was significant, $F(1, 15) = 10.28$, $p = .006$, $\eta_p^2 = .41$. The main effect of C2 salience was not significant, $F(1, 15) = 1.66$, $p = .22$, $\eta_p^2 = .10$ and the interaction between the two factors only approached significance, $F(1, 15) = 3.42$, $p = .08$, $\eta_p^2 = .19$, indicating that the C2-location effect tended to be larger when C2 was salient than when it was not salient, although it was significant in both conditions, $F(1, 15) = 8.95$, $p = .009$, $\eta_p^2 = .37$ and $F(1, 15) = 7.35$, $p = .02$, $\eta_p^2 = .33$, respectively.

Location effect for the first cue (C1)

We conducted an ANOVA with C1 location (same vs. different) relative to the target and C2 condition (absent, non-salient or salient) as within-subject factors.

Reaction times. The main effect of C1 location was significant, $F(1, 15) = 62.6$, $p < .0001$, $\eta_p^2 = .81$, with faster RTs when the target appeared at the same location as C1 than at a different location. The main effect of C2 condition was also significant, $F(2, 30) = 109.9$, $p < .0001$, $\eta_p^2 = .88$, indicating that RTs were faster when C2 was absent than when it was present, irrespective of whether it was salient or non-salient. The interaction between the two factors was significant, $F(1, 15) = 7.49$, $p = .002$, $\eta_p^2 = .33$. Follow-up analyses showed that the C1-location effect was larger when C2 was absent than when it was non-salient, $F(1, 15) = 15.68$, $p = .001$, $\eta_p^2 = .51$, or salient, $F(1, 15) = 9.02$, $p = .009$, $\eta_p^2 = .36$, with no difference between the latter two conditions, $F < 1$. Planned comparisons revealed that the C1-location effect was significant when C2 was absent, $F(1, 15) = 118.4$, $p < .0001$, $\eta_p^2 = .89$, when it was non-salient, $F(1, 15) = 40.5$, $p < .0001$, $\eta_p^2 = .73$, and when it was salient, $F(1, 15) = 23.5$, $p = .0002$, $\eta_p^2 = .61$.

Table 2. Mean reaction times (in milliseconds) and accuracy rates in Experiment 2 when the target appeared at the same vs. different location relative to the second cue when it was non-salient vs. salient (upper two rows) and relative to the first cue when the second cue was absent, non-salient or salient (lower three rows). Within-subject standard errors (Morey, 2008) are presented in parentheses.

		Reaction times (in ms)		Accuracy rates	
Cue	Second-cue condition	Same location	Different location	Same location	Different location
Second cue	Non-salient	533 (2.2)	573 (2.5)	98.4% (0.3%)	97.4% (0.3%)
	Salient	535 (3.3)	577 (2.8)	98.5% (0.4%)	96.4% (0.4%)
First cue	Absent	508 (2.5)	552 (2.7)	99.5% (0.4%)	97.3% (0.4%)
	Non-salient	542 (3.2)	573 (2.5)	98.1% (0.5%)	97.4% (0.3%)
	Salient	548 (3.5)	577 (2.8)	97.4% (0.4%)	96.4% (0.4%)

Accuracy. The main effect of C1 location, was significant, $F(1, 15) = 8.57$, $p = .01$, $\eta_p^2 = .36$ and so was the main effect of C2 condition, $F(2, 30) = 5.35$, $p = .01$, $\eta_p^2 = .26$, indicating that accuracy was highest when C2 was absent and lowest when C2 was salient. The interaction between the two effects was not significant, $F(2, 30) = 2.28$, $p = .12$, $\eta_p^2 = .13$. Planned comparisons showed that the C1 location effect was significant when C2 was absent, $F(1, 15) = 12.23$, $p = .003$, $\eta_p^2 = .45$ and when it was salient, $F(1, 15) = 4.67$, $p = .047$, $\eta_p^2 = .24$, but not when it was non-salient, $F = 1$.

Location effect for the first cue (when it shared the second cue's location)

We conducted an ANOVA with C1 location (same vs. different relative to the target) and C2 presence (present vs. absent) as within-subject factors, on trials in which the second cue, when present, shared the first cue's location.

Reaction times. The main effect of C1 location was significant, indicating that responses were faster when the target appeared at the same location as C1 than at a different location, $F(1, 15) = 82.75$, $p = .0001$, $\eta_p^2 = .85$. The main effect of C2 presence was not significant, $F < 1$, but the interaction between the two factors approached significance, $F(1, 15) = 4.12$, $p = .06$, $\eta_p^2 = .22$, indicating that the C1-location effect tended to be larger when C2 was present than when it was absent, 61 ms vs. 48 ms, respectively.

Accuracy. There was no speed accuracy trade-off. The main effects of both C1 location and C2 presence were non-significant, both *F*s <1, and so was the interaction between these factors, $F(1, 15) = 1.64$, $p = .10$, $\eta_p^2 = .10$.

Discussion

In Experiment 2 we tested the possibility that the residual benefit at the location of the first cue following capture by the second cue may reflect the fact that the second cue failed to capture attention on some trials. The results of Experiment 2 closely replicated the findings from Experiment 1. However, our manipulation of the second cue's salience did not produce any effect, except for a weak trend on the accuracy measure towards a larger spatial effect for the second cue when it was salient than when it was not. Since making C2 substantially more salient and more similar to the target should have increased the probability of it capturing attention, the findings of Experiment 2 strongly suggest that capture was already maximal in Experiment 1. We nevertheless conducted additional analyses to further test the failure-of-capture account.

We relied on the observation that responses to the target were overall slower when the second cue was present than when it was absent. In particular, it was the case when the target appeared at the location of the first cue. This is exactly what should be expected if the second cue captured attention to its location. We reasoned that if the residual benefit at the location of the first cue originated in a subset of trials on which the second cue failed to capture attention, these trials should resemble C2-absent trials. This account thus predicts that the fastest of these trials should be as fast as the fastest C2-absent trials.

We tested this prediction by plotting the distribution of the trials in which the target appeared at the same location as the first cue (excluding trials in which the second cue also appeared at the same location as the first cue) when the second cue was absent and when it was present. To do that, we used a vincentization procedure (Ratcliff, 1979): quantiles of RT distributions were computed for each participant, each summarising 10% of the cumulative RT distribution, and were then averaged to produce the group distribution (Rouder & Speckman, 2004). This nonparametric procedure was applied separately for C2-absent and C2-present trials. As is clear from Figure 4 (Exp.2) the fastest trials when C2 was present were slower than the fastest trials when it was absent. The statistical reliability of this finding was confirmed by a t-test for the fastest 10% trials between the two conditions, $t(15) = -7.24$, $p < .001$. The same analysis was performed for Experiment 1 and yielded similar results (Figure 4, Exp.1), $t(15) = -5.58$, $p < .001$. These findings invalidate the failure-of-capture alternative account.

Experiment 3

The results of the first two experiments suggest that when attention is shifted rapidly between two locations, its benefits can accrue to both locations simultaneously, at least for 100 ms. It is noteworthy that the longest inter-target interval used by Eimer and Grubert's

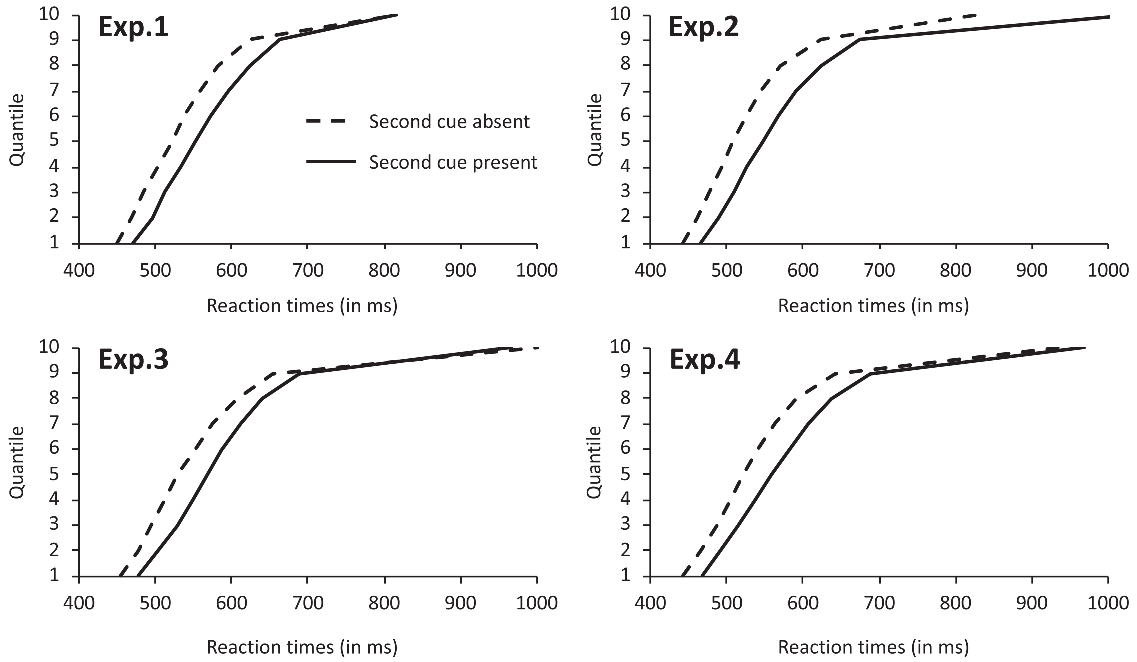

Figure 4. Vincentized reaction time distributions (quantile means) in the C2-absent and C2-present conditions, on trials in which the target appeared at the location of the first cue and not at the location of the second cue, in Experiments 1–4.

(2014) was also 100 ms and they also, reported evidence suggesting that attention can be allocated to the second target and simultaneously remain focused on the first during this interval. However, as explained earlier, our findings so far are not necessarily incompatible with a serial model of attention.

On the one hand, attentional shifting may be a relatively sluggish process, with attention being gradually deallocated from one location, while it is simultaneously reallocated to a new locus. According to this scenario, attention would move as one does across parallel (monkey) bars: one hand leaves the previous bar only after the other hand has secured its grip on the next bar: for a brief time, one holds two bars simultaneously. Sperling and Weichselgartner (1995; see also Shih & Sperling, 2002) suggested an episodic (quantal) theory of spatial attention that is compatible with this conceptualisation. They proposed that when attention moves from one location to the next, the spotlight pointed at the first location is extinguished and, simultaneously, the spotlight at the second location is turned on. They further posited that "because extinction and onset take a measurable amount of time, there is a brief period when the spotlights partially illuminate both locations simultaneously" (p.504).

On the other hand, variations in the speed of attentional shifting across trials or participants may spuriously generate the apparently simultaneous benefits observed at the locations of the two cues. Specifically, the 100-ms SOA between the second cue and the target may not suffice for completing the attentional shift away from the location of the first cue for all participants and on all trials. In line with this possibility, it has been suggested that a shift of attention between sequentially presented targets takes 150–200 ms (e.g., Moore et al., 1996; Woodman & Luck, 1999).

Both the above accounts predict that when the temporal interval between the second cue and the target is made longer[1] the residual spatial benefit at the location of the first cue should be eliminated while the spatial benefit at the location of the second cue should increase. The objective of Experiment 3 was to test this prediction. It was similar to Experiment 1, except that the SOA between the second cue and the target could be 100, 200 or 300ms[2].

Method

Participants

The participants were 16 (12 females, mean age = 22.87, *SD* = 2.39) Tel Aviv University undergraduate students, who participated in the experiment for course credit. All reported having normal or corrected-to-normal vision acuity and normal colour vision.

Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 1 except that the stimulus-onset asynchrony (SOA) between the second cue and the target (C2-target SOA) could take on three equiprobable and randomly mixed values, 100, 200 or 300 ms, instead of just one (100 ms) in the previous experiments and the number of experimental trials was increased to 960, divided into 12 blocks (as in Experiment 2).

Results

In all RT analyses, error trials (3.2% of all trials) as well as RT outliers (4.1%) were excluded. The mean location effects on RTs and accuracy data are presented in Figure 5. Mean RTs and accuracy scores are presented in Table 3.

Location effect for the second cue

We conducted an ANOVA on C2-present trials with C2-target location (same vs. different) and C2-target SOA (100, 200 or 300 ms) as within-subject factors.

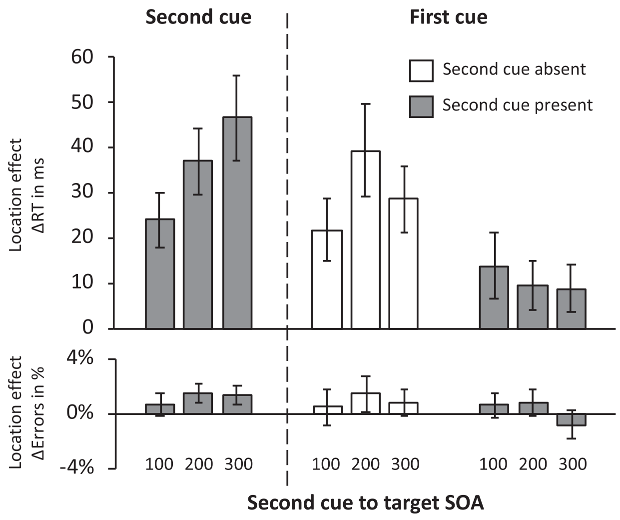

Figure 5. Mean location effect (different location minus same location) on reaction times (upper panel) and on error rates (lower panel) in Experiment 3, relative to the second cue (left) and relative to the first cue (right), as a function of the presence of the second cue (present vs. absent) and as a function of the stimulus-onset asynchrony (SOA) between the second cue and the target (100, 200, or 300 ms). Error bars denote within-subject standard errors (Morey, 2008).

Reaction times. The main effect of C2 location was significant, $F(1, 15) = 34.79$, $p < .0001$, $\eta_p^2 = .70$, with faster RTs on same- than on different-location trials and so was the main effect of SOA, $F(2, 30) = 6.24$, $p < .005$, $\eta_p^2 = .29$, with faster RTs the longer the SOA. The interaction between the two factors was significant, $F(2, 30) = 5.76$, $p = .008$, $\eta_p^2 = .28$, indicating that the C2-location effect increased as the SOA increased.

Accuracy

The main effect of C2 location was significant, $F(1, 15) = 7.50$, $p = .02$, $\eta_p^2 = .33$ and did not interact with C2-target SOA, $F < 1$.

Location effect for the first cue (C1)

We conducted an ANOVA with C1 location (same vs. different) relative to the target, C2 presence (present vs. absent) and C2-target SOA (100, 200 and 300 ms) as within-subject factors.

Reaction times. The main effect of C1 location was significant, $F(1, 15) = 21.29$, $p = .0003$, $\eta_p^2 = .59$, and so was the main effect of C2 presence, $F(1, 15) = 35.71$, $p < .0001$, $\eta_p^2 = .70$, with faster RTs when the target appeared at the same location as C1 than at a different location, and when C2 was absent than when it was present. The interaction between the two factors was significant, $F(1, 15) = 15.83$, $p = .001$, $\eta_p^2 = .51$, indicating that the C1-location effect was larger when C2 was absent than when it was present. Planned comparisons showed that the effect was significant in both conditions, $F(1, 15) = 24.83$, $p = .0001$, $\eta_p^2 = .62$ and $F(1, 15) = 8.02$, $p = .01$, $\eta_p^2 = .35$, respectively. The three-way interaction was not significant, $F(2, 30) = 1.57$, $p = .22$, $\eta_p^2 = .09$, suggesting that the presence of the second cue affected the C1-location effect to a similar extent across SOAs. However, planned comparisons showed that the C1-location effect only approached significance for each separate SOA, 14 ms, $F(1, 15) = 3.56$, $p = .08$, $\eta_p^2 = .19$ for the 100-ms SOA, 10 ms, $F(1, 15) = 3.03$, $p = .10$, $\eta_p^2 = .17$ for the 200-ms SOA, and 9 ms for the 300-ms SOA, $F(1, 15) = 2.92$, $p = .11$, $\eta_p^2 = .16$.

Again, vincentization of reaction times for trials on which the target appeared at the location of C1 revealed that the 10% fastest C2-present trials were significantly slower than the 10% fastest C2-absent trials, t(15) = 4.98, $p < .001$ (Figure 4, Exp.3).

Table 3. Mean reaction times (in milliseconds) and accuracy rates in Experiment 3 when the target appeared at the same vs. different location relative to the second cue as a function of the SOA between the second cue and the target (100, 200 or 300 ms) and relative to the first cue when the second cue was absent vs. present as a function of the SOA between the first cue and the target (200, 300 or 400 ms). Within-subject standard errors (Morey, 2008) are presented in parentheses.

			Reaction times (in ms)		Accuracy rates	
Cue	Second-cue condition	SOA	Same location	Different location	Same location	Different location
Second cue	Present	100	564 (5.3)	588 (3.5)	97.2% (0.6%)	96.5% (0.5%)
		200	554 (4.4)	591 (4.0)	98.1% (0.4%)	96.6% (0.5%)
		300	541 (5.0)	588 (6.0)	97.1% (0.5%)	95.8% (0.6%)
First cue	Absent	200	559 (6.1)	581 (4.1)	97.2% (0.8%)	96.7% (0.6%)
		300	544 (6.0)	583 (4.8)	97.6% (0.5%)	96.2% (0.9%)
		400	545 (4.9)	574 (3.5)	97.9% (0.7%)	97.1% (0.5%)
	Present	200	574 (4.9)	588 (3.5)	97.1% (0.9%)	96.5% (0.5%)
		300	581 (5.1)	591 (4.0)	97.4% (0.8%)	96.6% (0.5%)
		400	579 (4.3)	588 (6.0)	95.0% (0.8%)	95.8% (0.6%)

Accuracy. The main effect of C1 location did not reach significance, $F(1, 15) = 2.83$, $p = .11$, $\eta_p^2 = .16$ and was not involved in any significant interaction, all Fs < 1. Planned comparisons showed that the C1-location effect was significant when C2 was absent, $F(1, 15) = 4.60$, $p = .049$, $\eta_p^2 = .23$ but when not C2 was present, $F < 1$.

Location effect for the first cue (when it shared the second cue's location)

We conducted ANOVA with C1 location (same vs. different relative to the target) and C2 presence (present vs. absent) and C2-target SOA (100, 200 and 300 ms) as within-subject factors, on trials in which the second cue, when present, shared the first cue's location.

Reaction times. Only the main effect of C1 location was significant, indicating that responses were faster when the target appeared at the same location as C1 than at a different location, $F(1, 15) = 31.64$, $p = .0001$, $\eta_p^2 = .68$. The interaction between the C1 location and C2 presence was not significant, $F(1, 15) = 1.69$, $p = .21$, $\eta_p^2 = .10$. There was again a numerical trend towards a larger C1 location effect when C2 was present than when it was absent, 45 ms vs. 34 ms, respectively.

Accuracy. There was no significant effect. In particular, the interaction between C1 location and C2 presence was not significant, $F < 1$.

Discussion

As in the first two experiments, we observed a spatial benefit at the location of the first cue even after attention had been redirected to the second cue, and this effect was again reduced relative to when the second cue was absent.

The spatial benefit at the location of a single cue increased as the time between this cue's onset and the target's onset increased: the C2-location effect increased steadily from the 100- to the 300-ms SOA and so did the C1-location effect on C2-absent trials, from the 100- to 200-ms SOA (which correspond to the 100 and 200 ms second-cue-to-target SOAs in Figure 5, since the first cue appeared 100 ms before the second cue). Interestingly, this increase seemed to taper off when the cue-to-target SOA increased beyond 300ms: the C1-location effect did not increase further from 300 ms to 400 ms (which correspond to 200 and 300-ms SOAs in Figure 5). This pattern of results suggests that to the extent that establishing an attentional focus at a new location takes time (e.g., Shih & Sperling, 2002; Sperling & Weichselgartner, 1995), this process was completed within 300 ms in the present experiment.

On the one hand, the increase of the spatial benefit at the location of the second cue was not matched by a parallel increase of the impact of its presence on the spatial benefit at the location of the first cue: the C1-location effect when the second cue was present was unaffected by the SOA manipulation ($F < 1$). Thus, this finding further invalidates the notion that the residual effect at the location of the first cue resulted from occasional failures of the second cue to capture attention. If it were the case, one would have expected the residual effect to increase with SOA (as did the C1-location effect when the second cue was absent).

On the other hand, the residual effect did not disappear with long SOAs. Thus, the findings of Experiment 3 do not support the notion when attention is summoned to two successive locations, the attentional spotlight at the first location is slowly extinguished while a new spotlight is gradually lit at the second location. They are also unlikely to reflect individual or trial-by-trial variations in shifting speed because 300 ms would appear to provide enough time for completing an attentional shift (e.g., Moore et al., 1996; Woodman & Luck, 1999).

However, it is noteworthy that the residual spatial effect at the location of the first cue for the shortest second-cue-to-target interval (50 ms) was much smaller in this experiment than in the previous ones (14 ms vs. 27 and 20 ms in Experiments 1 and 2, respectively) and did not reach significance. Therefore, the effect of the SOA manipulation on the residual C1-location effect may not have reached significance due to floor effects. In addition, each cell of the design may not have included enough trials because we used three SOAs instead of just one, but less than doubled the number of trials (960 vs. 512 trials in Experiment 3 vs. 1, respectively). The objective of the next experiment was to address these potential problems.

Experiment 4

Experiment 4 was similar to Experiment 3 except for the following changes. The distance between objects in the display was made larger in order to increase spatial effects and prevent floor effects. In addition, only two C2-target (50 and 250 ms) intervals were used, thus effectively increasing the number of trials per cell.

Method

Participants

The participants were 16 (9 females, mean age = 23.12, *SD* = 2.5) Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal vision acuity and normal colour vision.

Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 3, except that the circles were distant from fixation by 5° centre-to-centre, instead of 2.8° and there were two C2-target SOAs (100 and 300 ms) instead of three.

Results

In all RT analyses, error trials (2.9% of all trials) as well as RT outliers (3.09%) were excluded. The mean location effects on RTs and accuracy data are presented in Figure 6. Mean RTs and accuracy scores are presented in Table 4.

Location effect for the second cue

Reaction times. The main effects of C2 location and C2-target SOA were both significant, with faster RTs on same- than on different-location trials, $F(1,\ 15) = 64.54$, $p < .0001$, $\eta_p^2 = .81$, and for the long than for the short SOA, $F(1,\ 15) = 19.74$, $p = .0005$, $\eta_p^2 = .57$. The interaction between the two factors was also significant, $F(1,\ 15) = 27.23$, $p = 0001$, $\eta_p^2 = .64$, indicating that the C2-location effect was larger at the long than at the short SOA.

Accuracy. The main effect of C2 location was significant, $F(1,\ 15) = 4.62$, $p = .048$, $\eta_p^2 = .24$ and its interaction with C2-target SOA approached significance, $F(1,\ 15) = 4.00$, $p = .06$, $\eta_p^2 = .21$, indicating that the C2-location effect tended to be larger at the long than at the short SOA.

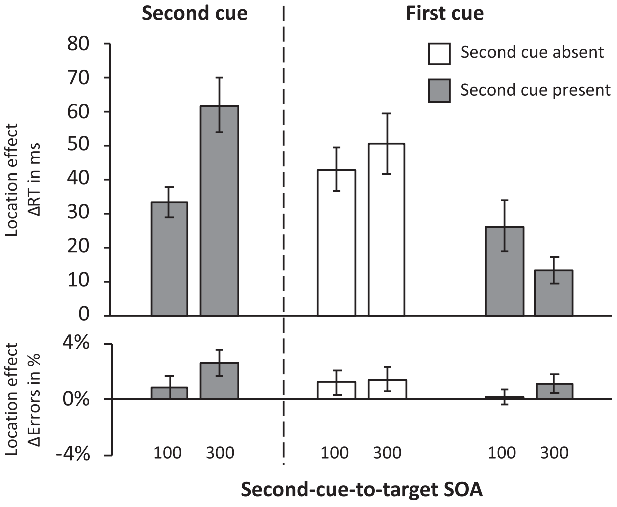

Figure 6. Mean location effect (different location minus same location) on reaction times (upper panel) and on error rates (lower panel) in Experiment 4, relative to the second cue (left) and relative to the first cue (right), as a function of the presence of the second cue (present vs. absent) and as a function of the stimulus-onset asynchrony (SOA) between the second cue and the target (100 or 300 ms). Error bars denote within-subject standard errors (Morey, 2008).

Table 4. Mean reaction times (in milliseconds) and accuracy rates in Experiment 4 when the target appeared at the same vs. different location relative to the second cue as a function of the SOA between the second cue and the target (100 or 300 ms) and relative to the first cue when the second cue was absent vs. present as a function of the SOA between the first cue and the target (200 or 400 ms). Within-subject standard errors (Morey, 2008) are presented in parentheses.

			Reaction times (in ms)		Accuracy rates	
Cue	Second-cue condition	SOA	Same location	Different location	Same location	Different location
Second cue	Present	100	551 (3.5)	584 (4.1)	98.1% (0.6%)	97.2% (0.4%)
		300	517 (4.9)	579 (3.7)	98.3% (0.6%)	95.6% (0.5%)
First cue	Absent	200	526 (4.9)	569 (2.6)	98.3% (0.8%)	97.1% (0.4%)
		400	516 (5.7)	567 (3.9)	98.2% (0.6%)	96.7% (0.4%)
	Present	200	558 (4.1)	584 (4.1)	97.5% (0.3%)	97.2% (0.4%)
		400	566 (6.0)	579 (3.7)	96.7% (0.7%)	95.6% (0.5%)

Location effect for the first cue (C1)

Reaction times. The main effects of both C1 location and C2 presence were significant, with faster RTs when the target appeared at the same location as C1 than at a different location, $F(1, 15) = 38.85$, $p < .0001$, $\eta_p^2 = .72$, and when C2 was absent than when it was present, $F(1, 15) = 50.26$, $p < .0001$, $\eta_p^2 = .77$. The interaction between C1 location and C2 presence was significant, $F(1, 15) = 38.42$, $p < .0001$, $\eta_p^2 = .72$, indicating that the C1-location effect was larger when C2 was absent than when it was present. Planned comparisons showed that the C1-location effect was significant in both conditions, $F(1, 15) = 43.7$, $p < .0001$, $\eta_p^2 = .74$ and $F(1, 15) = 23.9$, $p = .0002$, $\eta_p^2 = .61$, respectively. The three-way interaction did not reach significance, $F(1, 15) = 2.69$, $p = .12$, $\eta_p^2 = .15$. However, it is noteworthy that while the C1-location effect tended to increase as the SOA increased on C2-absent trials, it tended to decrease on C2-present trials, although neither of these numerical trends was significant, $\mathrm{F}(1, 15) = 1.46$, $p = 0.25$ and $\mathrm{F}(1, 15) = 2.33$, $p = 0.15$, respectively. Planned comparisons showed than the C1-location effect remained significant when C2 was present, both for the short SOA, $F(1, 15) = 12.8$, $p = .003$, $\eta_p^2 = .46$ and for the long SOA, $F(1, 15) = 12.6$, $p = .003$, $\eta_p^2 = .46$.

Again, vincentization of reaction times for trials on which the target appeared at the location of C1 revealed that the 10% fastest C2-present trials were significantly slower than the 10% fastest C2-absent trials, $\mathrm{t}(15) = 4.93$, $p < .001$ (Figure 4, Exp.4).

Accuracy. The main effect of C1 location was significant, $F(1, 15) = 11.16$, $p = .004$, $\eta_p^2 = .43$ and was not involved in any interaction, all $F\mathrm{s} < 1$. Planned comparisons showed that the C1 location effect approached significance when C2 was absent, $F(1, 15) = 4.07$, $p = .06$, $\eta_p^2 = .21$, and was non-significant when C2 was present, $F < 1$.

Location effect for the first cue (when it shared the second cue's location)

We conducted an ANOVA with C1 location (same vs. different relative to the target) and C2 presence (present vs. absent) and C2-target SOA (100, 200 and 300 ms) as within-subject factors, on trials in which the second cue, when present, shared the first cue's location.

Reaction times. The main effects of C1 location and C2-target SOA were significant, $F(1, 15) = 32.52$, $p < .0001$, $\eta_p^2 = .68$ and $F(1, 15) = 11.64$, $p = .004$, $\eta_p^2 = .44$, respectively and so were the interactions between C2 presence and C2-target SOA, $F(1, 15) = 6.28$, $p = .024$, $\eta_p^2 = .30$ and between C1 location and C2 presence, $F(1, 15) = 9.84$, $p = .007$, $\eta_p^2 = .40$. These effects were modulated by a significant three-way interaction, $F(1, 15) = 8.92$, $p = .009$, $\eta_p^2 = .37$. Separate analyses for each C2-target SOA indicated that the C1 location effect was significantly larger on C2-present than on C2-absent trials for the 250-ms SOA, 64 ms vs. 40 ms, $F(1, 15) = 14.7$, $p = .002$, $\eta_p^2 = .49$, but not for the 50-ms SOA, 45 ms vs. 43 ms, $F < 1$.

Accuracy. There was no speed accuracy trade-off. The mains effect of C1 location and C2 presence were significant, $F(1, 15) = 8.65$, $p = .01$, $\eta_p^2 = .36$ and $F(1, 15) = 4.56$, $p = .05$, $\eta_p^2 = .23$, respectively, but the main effect of C2-target SOA was not, $F(1, 15) = 2.50$, $p = .14$, $\eta_p^2 = .14$. No other effect approached significance, all $F\mathrm{s} < 1$.

Discussion

In Experiment 4, we were able to reinstate a residual spatial benefit at the location of the first cue for the

50 ms second-cue-to-target SOA, that was similar to the benefits obtained in similar conditions in Experiments 1 and 2 (26 ms vs. 27 and 20 ms in Experiments 1 and 2, respectively). All the main findings observed in Experiment 3 were replicated and were statistically more reliable. The spatial benefit at the location of the second cue increased as the SOA increased, and the residual benefit at the location of the first cue was highly significant at both the short and the long SOA. Thus, 300 ms after attention was captured by the second cue, responses to the target were still faster when it appeared at the location of the first cue, suggesting that attention was not yet fully disengaged from it. Again, despite a clear numerical trend, the residual C1-location effect did not decrease significantly when the second-cue-to-target SOA grew from 100 to 300 ms. In this regard, it is noteworthy that inspection of individual data revealed that 8 out of the 16 participants did not show a decrease in the residual C1-location effect when the SOA increased.

General Discussion

Summary of the findings

The objective of the present study was to investigate whether attention has to first be disengaged from a location before it can be moved to another. The results of four experiments suggest a negative answer to this question: we found a residual benefit at the location of a first cue even though attention had been shifted to a new location (second cue), suggesting that attention can be directed to a new location before it is entirely disengaged from its previous locus. We tested two alternative interpretations.

One is that the residual location effect may emanate from trials in which the second cue failed to capture attention. Several findings of the present study invalidate this account. First, a strong increase of second cue's physical salience only slightly modulated capture by the second cue (with a marginal effect on accuracy and none on RTs) and did not affect the residual benefit at the location of the first cue (Experiment 2). This finding suggests that capture by the less salient cue was already near ceiling, and strongly undermines the notion that it often failed to occur. Second, we showed that in all four experiments, the fastest trials in which the target appeared at the same location as the first cue were significantly faster when the second cue was absent than when it was present (Figure 4). If the second cue often failed capture attention, these trials should have been equally fast. Finally, we showed that the time course of the residual spatial effect was different from the time course of attentional capture (Experiments 3 & 4), suggesting that these effects did not index the same events: capture by the second cue – and to a lesser extent capture by the first cue when the second cue was absent – increased as the cue-to-target SOA increased, whereas the residual spatial benefit showed a non-significant trend in the opposite direction.

The second alternative interpretation is that the speed at which attention is reallocated from the second cue may vary cross participants or across trials: within 100 ms after the onset of the second cue, attention may still be focused on the first cue on some trials and already reallocated to the second cue on others. To examine this possibility, we varied the SOA between the second cue and the target from 100 to 300 ms. Although the residual spatial effect showed an unreliable tendency to decrease as the SOA increased, it remained highly significant when the SOA was as long as 300 ms. Taken together, these findings suggest that shifting attention from one location to another, results in two simultaneous foci of attention for at least 300 ms, and that the latest focus is more highly activated than the less recent one.

Relation to previous studies

Our findings are generally consistent with the outcomes of single-cell (Busse et al., 2008; Khayat et al., 2006) and ERP (Eimer & Grubert, 2014; Grubert & Eimer, 2016) studies, suggesting that attention can be maintained at the location of a first object after it was shifted to a different object. However, these studies did not provide any clue as to how long simultaneous enhancement at the two successive locations might last. Here, we found that a benefit is still clearly present 300 ms after attention is reoriented to a new locus. In addition, as pointed out by Busse et al. (2008), the impact on overt behaviour of the temporal asymmetry between suppression and enhancement (in single-cell studies) and of independent and additive N2pc components (in ERP studies) is not clear. For instance, Busse et al. (2008) reported a 120 ms delay between suppression at the old location and enhancement at the new one. The simple prediction following from this finding is that during this interval, no decrement in the spatial benefit accruing to the first location should be observed. Here, however, we found attentional benefits at the first locus to be reduced by about 50%, 100 ms after attention was reallocated to a new location. Future studies are thus required in order to bridge between neurophysiological and behavioural findings.

A notable difference between the present study and previous ones is that we examined allocation of attention to two successive objects that were not informative and had to be ignored (the cues), whereas previous studies investigated allocation to two successive targets. It is reasonable to assume that attention should take longer to disengage from a target, which has to be identified and encoded in working memory, than from an uninformative cue. Thus, residual benefits at the locus of a previous target are likely to be even larger and longer-lasting than the effects observed here for to-be-ignored cues. On the other hand, the cues used in the present study shared the target colour and attentional capture by these cues was therefore driven by their match with the observers' goals. Thus, whether residual attentional benefits also occur at the location of exogenous cues such as abrupt onsets, is unknown and the answer to this question awaits further research. Finally, in our study, both cues were defined along the same dimension: whether residual attentional benefits are observed when the two cues belong to different dimensions also remains an open question.

Split attention, inter-trial priming or biased competition?

An alternative interpretation of the residual spatial effects observed here is that they do not index allocation of attention but pre-attentive tagging. It has been suggested that prior to serial allocation of limited attentional resources, an early pre-attentive parallel mechanism can tag a number of non-contiguous loci (Bichot, Rossi, & Desimone, 2005; Kaptein, Theeuwes, & Van der Heijden, 1995; Luck & Hillyard, 1990), providing anchor points for the allocation of attention and location information for subsequent visual processes (Wright, 1994). According to the FINST theory (Pylyshyn, 1994; Pylyshyn & Storm, 1988), for instance, up to at least four objects can be tagged simultaneously at no cost, but extracting information from the tagged location requires serial allocation of attention. How might the location of the first cue be tagged to produce the residual spatial benefit observed here?

Inter-trial position priming. One possibility is that the residual spatial benefit reflects a relatively long-lasting effect of previous selection, known as inter-trial position priming. Inter-trial position priming refers to the finding that in search tasks, a target on a given trial is responded to faster it appears at the location of the previous target than at the location occupied by either a distractor or empty space on the previous trial (e.g., Geyer, Müller, & Krummenacher, 2007; Hilchey, Leber, & Pratt, 2018; Maljkovic & Nakayama, 1996; Yashar & Lamy, 2010). Most relevant to the present purposes, position priming is not limited to the previous target location: the position of a target a few trials earlier can exert its influence on the current trial (Maljkovic & Nakayama, 1996). The implication of this is that focusing attention at a location speeds performance to a target appearing at the same location a few trials ahead, although attention was shifted to different locations during intermediate trials. This effect is thus similar to the residual benefit we observed here, albeit over much longer temporal intervals.

Inter-trial priming effects were found to be strongly modulated by response repetition: repeating the target location speeds performance when the prior response repeats, yet this effect is much smaller, if at all present, when the prior response changes (e.g., Gokce, Geyer, Finke, Müller, & Töllner, 2014; Gokce, Müller, & Geyer, 2015; Hilchey et al., 2018). Unlike the foregoing studies, which all investigated target-target spatial repetitions, we examined cue-target spatial repetitions. Thus, if inter-trial position priming benefits occur at the stage of response selection, as its interaction with response repetition suggests, this effect indexes mechanisms that are unrelated to the residual location effect reported here, since our cues were never responded to (nor were they associated with a response feature). However, it has been suggested that inter-trial position priming is a multi-process effect, with part of the effect being independent of responses processes (e.g., Hilchey et al., 2018). Thus, the residual location effect observed here may reflect the same mechanism as the response-independent portion of inter-trial position priming.

Spatial cueing effects as a manifestation of biased competition. Another possibility relies on the conjecture that spatial cueing (or location) effects may not necessarily index shifts of attention. If spatial cuing effects indeed indicate that a limited resource (or spotlight) was shifted to the cue, it is difficult to explain why this limited resource is maintained at an uninformative location for more than 400 ms (e.g., on C2-absent trials), when the most adaptive behaviour would be to return attention to the centre of the screen or to distribute it across the search display. Recently, Lamy, Darnell, Levi, and Bublil (2018) put forward an alternative interpretation of spatial cueing effects within a *priority-accumulation framework* that draws from Desimone and Duncan's (1995) biased competition model. According to this framework, several factors determine the attentional priority level of a given location in a search display, and one of these factors is whether a potentially important object (here, the cue, i.e., a salient item sharing the target colour) recently appeared there. Attentional priority weights are summed across time until the search context (e.g., the search display) signals that selection can occur: the item in the search display to which the first attentional shift is made is the item that wins the competition (i.e., the item with the highest attentional priority). However, how long it takes for the competition to be resolved varies as a function of how large the winner's leading edge is. Thus, according to this framework, spatial cueing effects do not index allocation of focused attention per se, but instead provide information about the extent to which a cue biases the competition in favour of the target when it appears at its location rather than at the location of a non-target.

This framework is compatible with the present findings. Priority accumulation takes time to reach its asymptotic level following the occurrence of a salient event, which explains the increasing spatial cueing benefits observed here as the SOA increased. Activation remains high until the search event occurs, which explains why spatial cueing benefits are observed as long as 400 ms after cue onset. In addition, more priority accrues to the more recent events, which explains why the spatial cueing benefit was larger at the location of the second cue than at the location of the first cue, across experiments and across SOAs. Finally, stronger activation accrues to a location the more potentially important events occur at its location which explains why, across all four experiments, the spatial cueing benefit associated with the first cue tended to be larger when the second cue shared its location than when this cue was absent.

According to this conceptualisation of spatial cueing effects, our findings do not entail that attention, that is, the selective enhancement of processing at a given location, was split between two different locations, because it is assumed that attention was not shifted to the cue's location in the first place. However, it is important to keep in mind that the main evidence on which the priority accumulation framework is based emanated from stimulus-driven spatial cueing effects (with abruptly onset cues not sharing the target colour, see Lamy et al., 2018 for details). Recent research suggested that stimulus-driven and goal-directed attentional capture have qualitatively different consequences on the deployment of attention and that only cues sharing the target-defining feature elicit mandatory shifts (and engagement) of attention (Zivony & Lamy, 2018; see also Zivony et al., 2018). Thus, whether the present findings reflect parallel allocation of attention to separate locations cannot be resolved before further research clarifies whether detecting the target feature immediately and automatically triggers attentional selection (in the cueing display and regardless of whether the target-feature object actually is the target, as is usually assumed, e.g., Folk et al., 1992) or only speeds the selection of the target when it appears at the cued location (in the search display, as suggested by Lamy et al., 2018).

Conclusions

The findings of the present experiments suggest that attention can be rapidly directed to a new object, even before it disengaged from the previously attended object. This conclusion is incompatible with the claim that attention operates as a strictly serial spotlight (Posner et al., 1980). It is also inconsistent with the variant of the spotlight model suggested by Sperling and colleagues (Shih & Sperling, 2002; Sperling & Weichselgartner, 1995), according to which extinction and onset of successive spotlights occurs gradually within a 200-ms window. Instead, the present findings suggest that shifting attention from one location to another result in two simultaneous foci of attention. However, it will be important to further test this conclusion in future research by clarifying (1) the role of position priming and (2) whether goal-dependent spatial cueing effects reflect shifts of attention to the cue (in line with contingent capture account, e.g., Folk & Remington, 1998) or pre-attentive tagging of the cued location.

Notes

1. Note that the temporal interval between the second cue and the target rather than between the first cue and the target is the relevant interval to manipulate in order to test this prediction. Only after attention is shifted to the location of the second cue can it start to be deallocated from the location of the first cue.
2. We did not expect this manipulation to yield inhibition of return (IoR, Posner & Cohen, 1984), that is, delayed response latencies at the location of the fist cue after attention was shifted to the second cue, because IoR is typically observed with abrupt onsets and not with color singletons and with longer inter-stimulus, typically over 800 ms (e.g., Pratt, Sekuler, & McAuliffe, 2001 but see Priess, Born, & Ansorge, 2012, for evidence of IoR with color singletons using eye movements).

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