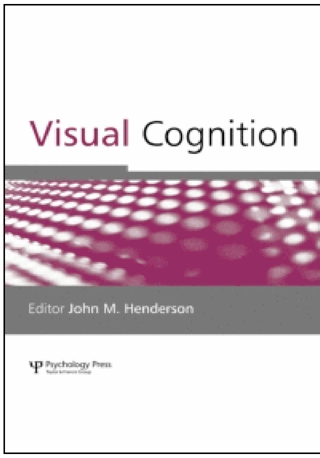

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Transient spatial attention and the perceived duration of brief visual events

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Transient spatial attention and the perceived duration of brief visual events

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This study was designed to explore the effects of transient attention—the stimulus-driven component of spatial attention—on the perceived duration of a brief visual event. Observers had to compare the duration of two disks presented successively within a single trial. The disks' location and duration varied independently. One of these disks, the "attended disk", was preceded by an attentional cue indicating the disk's location, attracting transient attention in advanced to the disk location. This attentional cue was either a typical onset cue (Experiments 1, 2, and 4) or a singleton cue (Experiment 3) that minimized the differences between the cues. The other disk, the "neutral disk", was cued with a neutral cue that did not convey information regarding the disk location. We found that the attraction of transient attention to the location of the attended disk prolonged its perceived duration, but only when compared to brief nonattend stimuli.

Spatial covert attention allows us to selectively attend to the location of relevant information without eye movements to that location. A large body of evidence suggests that spatial covert attention has two components: "sustained" and "transient". Sustained attention is a conceptually driven component that is allocated to a location according to our goals and requires conscious effort. It is the relatively slow component that is activated in about 300 ms. Transient attention is a stimulus-driven component that is typically attracted to a location by sudden changes in the visual display. It is a faster component that is activated in an automatic manner in about 100 ms (e.g., Cheal & Lyon, 1991; Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Remington, Johnston, & Yantis, 1992). Additionally, transient attention is considered to operate at an earlier stage of visual cortical

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processing than sustained attention (e.g., Nakayama & Mackeben, 1989). Indeed, neurophysiological studies suggest that whereas sustained attention is cortical in nature, transient attention is mediated by both cortical and subcortical networks (Corbetta & Shulman, 2002; Kastner & Ungerleider, 2000). The goal of this study was to explore the effects of the transient component of spatial attention on the perceived duration of a brief visual event. In particular, this study evaluated whether the allocation of transient attention to the target location leads to an overestimation of the target duration, an underestimation, or does not affect duration judgements.

The role of attention in time perception, and specifically its effects on the perceived duration has been studied extensively in the past (e.g., Block, 1992; Casini & Macar, 1997; Fortin, Rousseau, Bourque, & Kirouac, 1993; Hicks, Miller, Gaes, & Bierman, 1977; Hicks, Miller, & Kinsbourne, 1976; Macar, 1996; Macar, Grondin, & Casini, 1994; Zakay, 1998). Macar (1996), for instance, employed a dual-task paradigm involving a temporal component—reproduction of duration, and a nontemporal component—word categorization. Attention was manipulated indirectly by manipulating the complexity of the word categorization task, assuming that the higher the complexity the less attentional resources would be allocated to the temporal task. In a similar paradigm but with a more explicit control over attention allocation, Macar et al. (1994) asked observers to control the amount of attention that they devote to each component of the dual-task paradigm. The finding of both studies, and many other dual-task studies, was that the perceived duration shortened as the amount of attention allocated to the temporal task diminished. Most of this work, however, did not manipulate spatial attention. Moreover, it has been suggested that the system mediating the perception of very brief durations—in the milliseconds (ms) range—is different than the system mediating the perception of longer durations—in the seconds and minutes range (e.g., Hazeltine, Helmuth, & Ivry, 1997; Ivry, 1996; Lewis & Miall, 2003; Marzi, 2004; Rammsayer, 1999). The former may rely on automatic mechanisms without cognitive control while the latter may require active processing under direct cognitive control (e.g., Mitriani, Shekerdijiiski, Gourevitch, & Yanev, 1977; Rammsayer, 1999; Rammsayer & Lima, 1991; but see Rammsayer & Ulrich, 2005). In light of this "two-systems" hypothesis and the fact that most of the dual task studies involved relatively long temporal durations, it is not clear whether their findings regarding the effects of attention on the perceived durations can be generalized to brief intervals.

Recently, several studies have extended the study of time perception and attention to visual events of relatively brief durations. In most cases, these studies have shown that attention prolongs the perceived duration. For instance, a couple of studies have demonstrated that unexpected stimuli are judged as longer than expected stimuli (Tse, Rivest, Intriligator, & Cavanagh, 2004; Ulrich, Nitschke, & Rammsayer, 2006). In these studies, two (Ulrich et al., 2006) or several (Tse et al., 2004) stimuli were presented successively at the centre of the display, and the observers had to compare their duration. The main manipulation, in both studies, was of appearance frequency—some stimuli appeared more frequently than others. Both studies found that the less frequent stimuli were judged as having a longer duration than the frequent stimuli. To the extent that attention is attracted to the unexpected stimuli, these findings would suggest that attention prolongs the perceived duration. Other studies have used an attentional cue—an arrow presented at the centre of the display—to guide attention to the stimulus location (e.g., Enns, Brehaut, & Shore, 1999; Mattes & Ulrich, 1998). This attentional cue indicated one of the possible locations and was followed by a successive presentation of two stimuli—one appearing at the cued location and the other at a noncued location. The observers were asked to compare the duration of the two stimuli. Both studies have found that the stimulus at the cued location had a longer perceived duration, suggesting that directing attention to the stimulus location prolonged the perceived duration. These studies, however, did not directly manipulate transient spatial attention. In particular, Ulrich et al. (2006) and Tse et al. (2004) did not manipulate spatial attention at all. Their studies did not introduce any spatial uncertainty regarding the relevant location, as the stimuli were always presented at the centre of the display. Consequently, spatial attention was always directed at the stimulus location regardless of the stimulus' appearance frequency, and their findings probably reflect the effects of feature-based attention or possibly, as Ulrich et al. suggest, a more general changes in arousal levels. Mattes and Ulrich (1998) and Enns et al. (1999) did manipulate spatial attention, but the attentional cues they used most probably trigger sustained attention—the more controlled component of spatial attention (e.g., Jonides, 1981; Nakayama & Mackeben, 1989; Posner, 1980).

The only study that combined measurements of the perceived duration and manipulation of transient attention is the study by Chen and O'Neill (2001). In this study both the transient and sustained components of spatial attention were manipulated as well as object-based attention and the processing load. The basic display was composed of two rectangles. The target was either an "O" or an "X" and it could appear in one of four possible locations corresponding to the ends of the two rectangles. Target presentation was preceded by a spatial cue indicating one end of one of the rectangles. Thus, the target either appeared at the cued location, an uncued location within the cued rectangle, or an uncued location in an uncued rectangle. The cue was either an exogenous cue, attracting transient attention to its location (Experiments 1–2), or an endogenous cue, directing sustained attention to one of the possible locations (Experiments 3–4). Observers were asked to rate the duration of the target (i.e., categorize it as short, medium, or long), and this rating task was either a single primary task or a secondary task to the additional task of letter discrimination (Experiments 2 and 4 or 1 and 3, respectively). In contrast to previous studies (e.g., Enns et al., 1999; Mattes & Ulrich, 1998), Chen and O'Neill found that attention prolonged the perceived duration only when the duration rating was a secondary task. When the duration rating was a single task the target was judged as shorter when it appeared at the cued location. These results were found for both components of spatial attention, and there were no object-based effects on the perceived duration. Chen and O'Neill did not provide a detailed account of the difference between their findings and others, but they suggested that it is related to the fact that their target was a letter, which might encourage the higher processing of its meaning even when it was not required.

In sum, several studies have found that attention prolongs the perceived duration of brief events (e.g., Enns et al., 1999; Mattes & Ulrich, 1998; Tse et al., 2004; Ulrich et al., 2006), and although these studies did not manipulate transient attention, they suggest that a direct manipulation of transient attention should also lead to a prolonged perceived duration. Chen and O'Neill (2001), on the other hand, found that when duration judgement is the only task, both transient attention and sustained attention shorten the perceived duration. Given the contradictory nature of these findings, it is hard to predict the effects of transient attention on the perceived duration based on previous studies. This study reexamines the effects of transient attention on the perceived duration of very brief visual stimuli (in the ms range) under the following conditions: (a) A single task paradigm in which the task of duration judgement—a comparison of the duration of two successive stimuli—is the only task; (b) the visual display is simple—a single disk serving as the target, to avoid undesired nontemporal processing; and (c) transient attention is manipulated directly with peripheral precues. Given these measures, we expected the perceived duration to be longer when transient attention was focused on the disk location.

EXPERIMENT 1

Experiment 1 examined whether transient spatial attention can affect the perceived duration, in particular whether transient attention will prolong or shorten the perceived duration when duration judgement is the sole task. To examine this question, observers had to compare the duration of two brief disks presented one after the other. The disks' duration varied independently (at the range of 23–94 ms). One of these disks, the *attended disk*, was cued with an attentional peripheral cue indicating the disk location in advance.

Such a peripheral cue is considered to capture transient attention in a stimulus-driven, "automatic" manner (e.g., Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980; Yantis, 1996). The other disk, the *neutral disk*, was cued with a neutral cue that did not convey information regarding the disk location. To avoid response biases, half of the observers had to indicate which of the two disks was presented for a shorter duration and the other half had to indicate which disk had a longer duration.

Method

Observers. Fifteen students from the University of Haifa participated in this experiment; all were naive to the purpose of the study, and had normal or corrected to normal vision.

Stimuli and apparatus. The stimuli were presented on a 21-inch monitor of a PowerMac G4 computer. The grey disks had a diameter of 3° and were presented in one of 24 possible locations at one of 4 possible eccentricities (2°, 5°, 8°, 12°). The peripheral cue was a $0.7 \times 0.3°$ green horizontal bar appearing 0.3° above the attended disk location. The neutral cue was a 0.4° green circle appearing in the centre of the display indicating that the target could appear in any one of the possible locations.

Procedure. Each trial included two intervals (Figure 1). Each interval began with a fixation mark (750 ms) followed by a cue (50 ms) and an ISI (50 ms). Following the cue and its ISI, the disk appeared for a varying duration (23, 47, 70, 94 ms). These brief durations ensured that eye movements could not occur between cue onset and target offset (e.g., Mayfrank, Kimmig, & Fischer, 1987). On a random 50% of the trials, the first cue was a peripheral cue—indicating the disk onset and spatial location, and the second cue was neutral—indicating the disk onset but not its location. On the rest of the trials the first cue was neutral and the second peripheral. The disks' duration and location were chosen randomly and independently for each disk. Half of the observers had to indicate which one of the two disks appeared for a shorter duration, and the rest had to report which disk had a longer duration. Each observer viewed 50 practice trials and 768 experimental trials presented in a randomized order.

Results and discussion

To analyse the data we first estimated the point of subjective equality (PSE) by fitting a Weibull function (Weibull, 1951) to the data of each observer in each of the possible durations of the neutral disk. The PSE is defined as the point at which the attended disk was judged as having a longer duration than

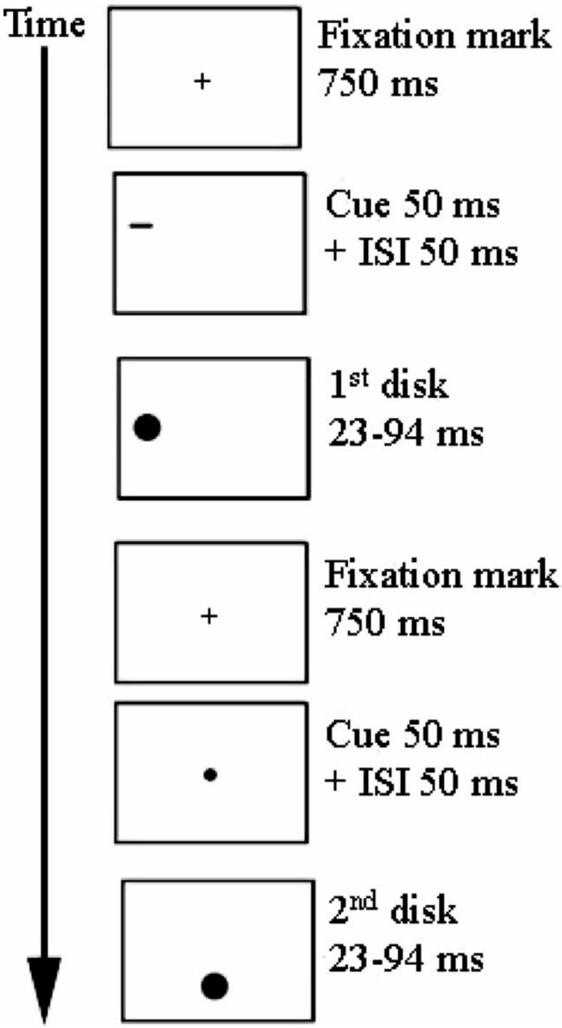

Figure 1. The sequence of events in a single experimental trial of Experiment 1.

the neutral disk on 50% of the trials. This is the point at which the attended and neutral disks are perceived as having an equal duration. For example, as can be seen in Figure 2, the PSE of observer HG, with neutral disk duration of 47 ms, was equal to 29 ms. That is, for this specific observer, an attended disk with a duration of 29 ms would appear equal in duration to a neutral disk with a duration of 47 ms.

Then, to be able to compare attentional effects with disks of different durations, we divided the duration of the neutral disk by its estimated PSE.

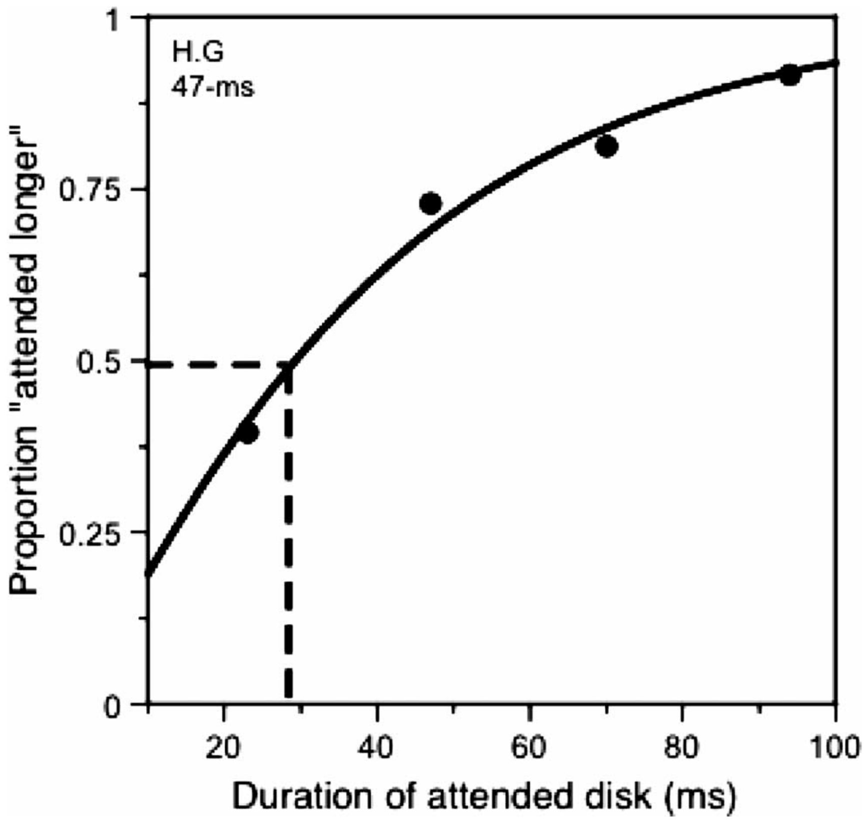

Figure 2. An example of PSE estimation in Experiment 1 for observer HG with neutral disk duration of 47 ms. The figure depicts the proportion of "attended disk longer" response as a function of the duration of the attended disk. The estimated PSE is marked by the dotted line, extending from the point of 0.5 proportion of "attended longer" response (i.e., "attended longer" and "neutral longer" responses are equally likely) to the fitted function.

If the resulting quotient is equal to 1, directing attention to the target location does not affect the perceived duration. But if it is higher than 1, attending the target location prolongs its perceived duration and vice versa. A *t*-test on this quotient, calculated across all observers, indicated that it was significantly higher than 1, $t(14) = 2.256$, $p < .05$, suggesting that the attended disk was perceived as having a longer duration than its actual physical duration. Interestingly, as can be seen in Figure 3, this quotient was higher than 1 only with neutral disk durations shorter than 94 ms. This finding is further explored in Experiment 2. There was no significant difference in this quotient between observers who had to report which disk was longer and those that had to report which disk was shorter. The lack of

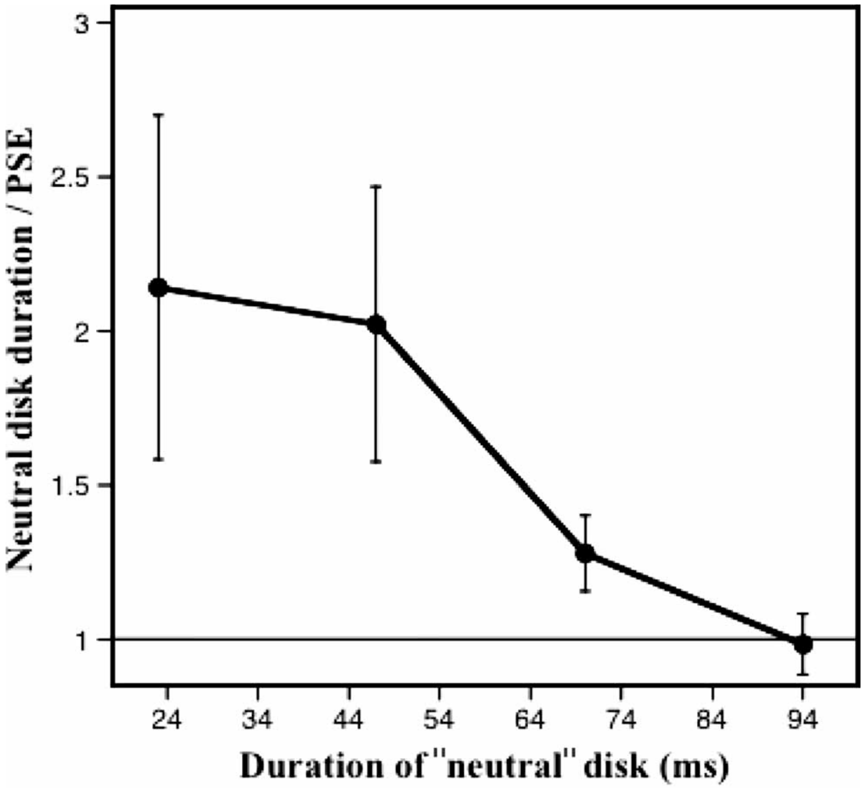

Figure 3. Experiment 1: The duration of the neutral disk divided by its estimated PSE as a function of the neutral disk duration. Error bars correspond to one standard error.

such significant difference suggests that our finding of a quotient higher than 1 is not due to a bias to report the attended disk, because such a bias should have resulted in a quotient that is smaller than 1 with the "report shorter" task. Finally, the quotient did not vary significantly as a function of target eccentricity.

Thus, when transient attention is attracted to the disk location by a peripheral cue, and observers are required to perform a single task—compare the duration of brief, simple visual stimuli—the perceived duration of the attended disk was prolonged. This finding is consistent with several previous studies that manipulated other components of visual attention such as sustained attention and feature-based attention (e.g., Enns et al., 1999; Mattes & Ulrich, 1998; Tse et al., 2004; Ulrich et al., 2006), and it suggests that transient attention also prolongs the perceived duration. However, the findings of these various studies, as those of Experiment 1, are not consistent with the findings of Chen and O'Neill (2001) that attending the target location shortened (rather than prolonged) the perceived duration when the duration judgement was a single task. Chen and O'Neill suggested that their findings might be due to the fact that the targets in their study were meaningful stimuli—letters—that possibly encouraged automatic reading, and such higher, nontemporal processes led to the shortened perceived duration. Another reason for this inconsistency could be the different nature of the duration judgement tasks employed by the different experiments. In Experiment 1 and several previous studies (e.g., Enns et al., 1999; Mattes & Ulrich, 1998; Tse et al., 2004; Ulrich et al., 2006) the observers had to compare the perceived duration of two or more stimuli within a single experimental trial, with a minimal need to relay on memory. In Chen and O'Neill's study the observers were asked to categorize the duration of the target as short, medium, or long, based on memorized representation of these three duration categories formed in a preexperiment learning phase. Thus, their findings may reflect a mixture of attentional effects on perceptual and memory processes.

EXPERIMENT 2

The attentional prolongation of the perceived duration found in Experiment 1 was only present when the duration of the neutral disk was shorter than 94 ms (Figure 3). One possible explanation for this finding is that the onset of the neutral disk also attracts attention, and when the duration of the neutral disk is long enough, there is enough time for the attentional mechanism to focus on the neutral disk. This would minimize the effects of attention because both disks are attended. Alternatively, this finding is simply due to the fact that 94 ms was the longest duration value within the range of disk durations employed in Experiment 1. To test whether the latter explanation can account for the absence of attentional effects with long neutral durations, we repeated the basic design of Experiment 1, but with longer durations (23–165 ms). If the lack of attentional prolongation with the duration of 94 ms is merely an outcome of the specific range of durations used in Experiment 1, attentional prolongation should be found for all the durations tested apart for the longest one—165 ms.

Method

Observers. Seventeen students from the University of Haifa participated in this experiment; none of them participated in the previous experiment. All of the observers were naive to the purpose of the study, and had normal or corrected to normal vision.

Stimuli, apparatus, and procedure. The stimuli, apparatus, and procedure were identical to Experiment 1 except for the following: The grey disks were presented in one of 12 possible locations at one of three possible eccentricities (2°, 5°, 8°). The disks appeared for a varying duration (23, 47, 82, 118, 165 ms). Each observer viewed 50 practice trials and 600 experimental trials presented in a randomized order.

Results and discussion

To analyse the data we estimated again the PSE by fitting a Weibull function (Weibull, 1951) to the data of each observer in each possible duration of the neutral disk, and then divided the duration of the neutral disk by its PSE. A *t*-test on this quotient, calculated across all observers, indicated that it was significantly higher than 1, $t(16) = 2.688$, $p < .009$. Additionally, as in Experiment 1, there was no significant difference in this quotient between the "report longer" and "report shorter" tasks, and it did not vary significantly as a function of eccentricity. Thus, the attentional prolongation of perceived duration, found in Experiment 1, was replicated here.

Most importantly, as can be seen in Figure 4, this quotient was higher than 1 only with neutral disk durations shorter than 118 ms. This finding suggests that the lack of attentional prolongation with neutral disk duration longer than $\sim$100 ms is not an artifact of the specific range of durations employed in Experiment 1, but reflect a real constraint on the emergence of this prolongation effect when the duration of the neutral disk is $\sim$100 ms or longer. As we suggested above, it is possible that with such long duration attention has enough time to also focus on the neutral disk, so that a substantial part of the processing of the neutral disk takes place under partial or even full attentional resources, and therefore, diminishes differences between the attended and neutral disks. This possibility is especially viable given the simplicity of the stimuli employed in our experiment. When the neutral disk appears it is the only stimulus present, and therefore its onset should be a powerful attractor of attention. Moreover, because it is the sole stimulus, focusing attention on its location should be relatively easy and possibly faster than in more cluttered displays.

EXPERIMENT 3

One possible interpretation of the findings of Experiments 1 and 2 is that the prolonged perceived duration merely reflects the combined perceived duration of the cue and the disk rather than a truly longer perceived duration of the attended disk. That is, because the peripheral cue appeared in an adjacent location to the attended disk, observers' decision

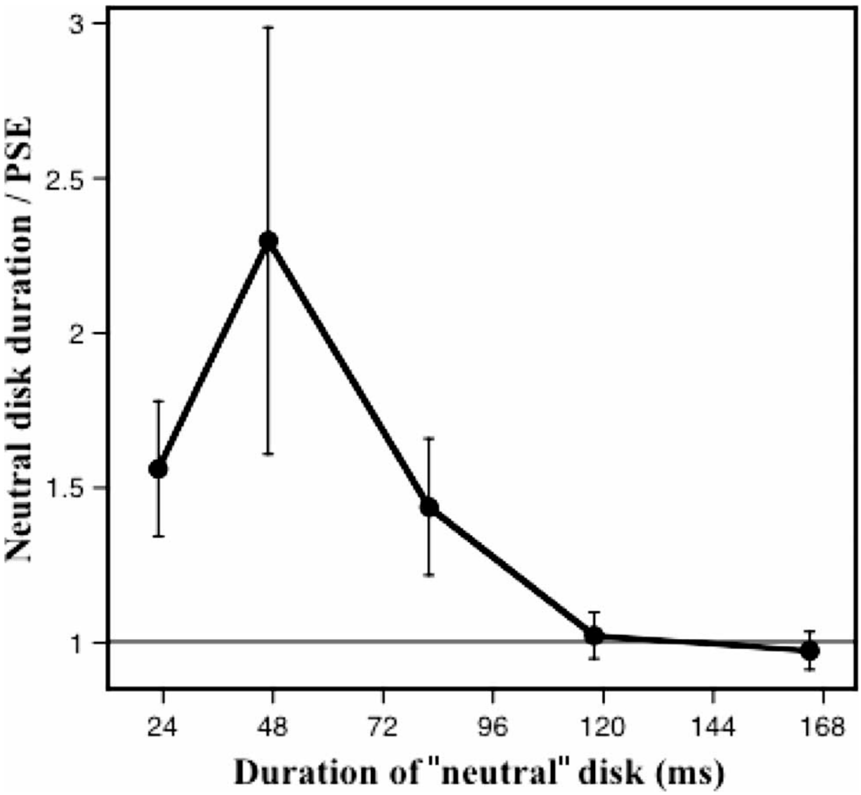

Figure 4. Experiment 2: The duration of the neutral disk divided by its estimated PSE as a function of the neutral disk duration. Error bars correspond to one standard error.

regarding the duration of the attended disk might have been based on the combined duration of the cue and disk rather than just that of the disk, as if the local neural response to the cue is added to the neural response to the disk. Experiment 3 was designed to rule out this alternative explanation. It was similar to Experiment 2, but it employed different cues. The cues in this experiment were multibar cues, composed of several small horizontal bars appearing above each of the possible locations. Each of these bars was similar to the bar used as the peripheral cue in Experiments 1 and 2. In the neutral cue all of the bars were green. A similar multibar neutral cue was employed successfully in previous studies (Talgar, Pelli, & Carrasco, 2004; Yeshurun, 2004). In the attentional cue, the bar appearing above the attended disk location was red and the other bars, appearing above the other possible locations, were green. The single red bar is considered a colour singleton capable of attracting transient attention to its location (e.g., Theeuwes, 1991), though not as efficiently as the cue onset of Experiments 1 and 2 (e.g., Irwin, Colcombe, Kramer, & Hahn, 2000). Because the only difference between the attentional and neutral cues in this experiment is the colour of the bar above the disks (i.e., red above the attended disk and green above the neutral disk), they should both lead to the same local interactions, if at all. Thus, if the prolonged perceived duration of attended disk, found in Experiments 1 and 2, was merely due to such local interactions it should not be found in this experiment. Alternatively, if this prolonged perceived duration is due to the advanced allocation of attention to the disk location, regardless of the kind of attentional cue that attracted attention, it should be found even with the singleton attentional cue employed here.

Method

Observers. Thirty-three students from the University of Haifa participated in this experiment; none of them participated in the previous experiments. All of the observers were naive to the purpose of the study, and had normal or corrected to normal vision.

Stimuli, apparatus, and procedure. The stimuli, apparatus, and procedure were similar to Experiment 2 except for the following changes: The disks could appear in one of six possible locations at 5° of eccentricity. The neutral cue was composed of six $0.7 \times 0.3^\circ$ green horizontal bars appearing 0.3° above each of the six possible locations. The attentional cue was identical to the neutral cue, but instead of six green bars it was composed of five green bars and one red bar. The bar above the attended disk location was red and the bars above the other possible locations were equal-luminance green.

Results and discussion

As in Experiments 1 and 2, to test whether or not transient attention affected the perceived duration, we estimated the PSEs for each observer and each possible duration of the neutral disk, and then divided the duration of the neutral disk by its corresponding PSE. The average of this quotient was once again significantly higher than 1, $t(32) = 2.3$, $p < .02$ (Figure 5), and it did not vary significantly between the tasks (i.e., "report longer" vs. "report shorter"). Hence, transient attention prolonged the perceived duration of the attended disk even when it was attracted to the cued location by a singleton cue that was identical to the neutral cue apart for the colour of the bar above the cued location. Although a smaller prolongation effect is expected with the singleton cue in comparison to the onset cue of Experiments 1 and 2,

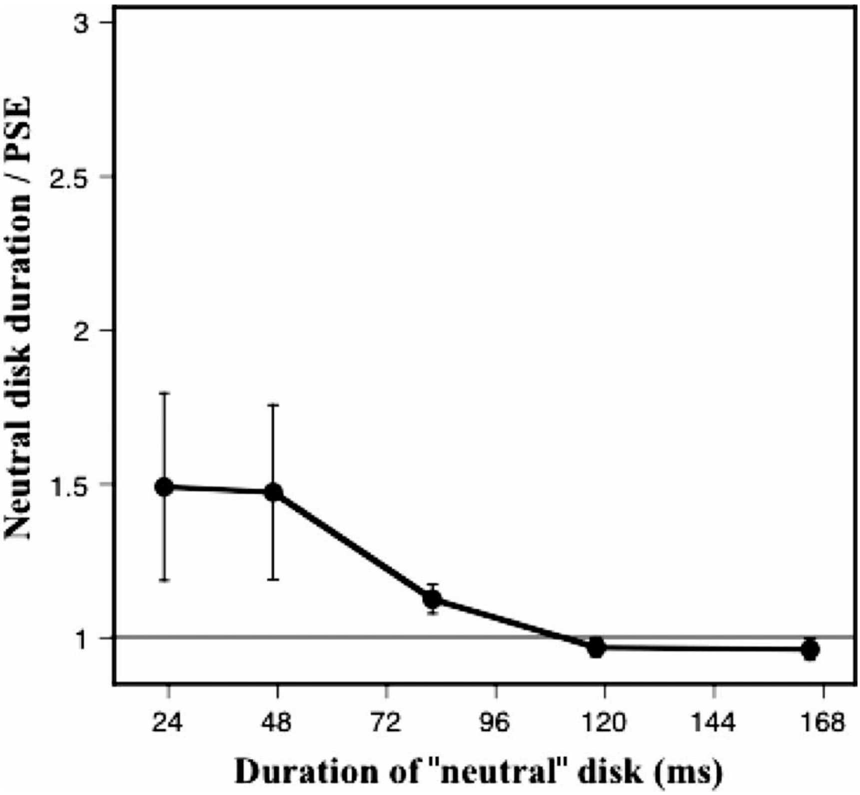

Figure 5. Experiment 3: The duration of the neutral disk divided by its estimated PSE as a function of the neutral disk duration. Error bars correspond to one standard error.

because a singleton is a less efficient attractor of transient attention (e.g., Irwin et al., 2000), a one-way ANOVA on the combined data of Experiments 2 and 3 (with "experiment" as a between variable) indicated that there was no significant difference between the "neutral duration/PSE" quotient of these two experiments ($p > .1$). Thus we were able to replicate the findings of Experiments 1 and 2 even with the less efficient "singleton-cue" and the multibar neutral cue that ensured the local information surrounding the attended and neutral disks is similar. Given that the colour of the bar above the cued location was the only difference between the attentional and neutral cues, we can conclude that the prolonged perceived duration of the attended disk is indeed due to the advanced allocation of transient attention to the location of the attended disk rather than a mere local integration of the cue and disk durations.

EXPERIMENT 4

In Experiments 1–3 the attentional cue indicated the disk location with 100% validity. Given that the attentional cue was informative, the observers of these experiments might have also voluntarily attended the cued location. If so, the attentional effects found in Experiments 1–3 reflect some mixture of transient and sustained attentional effects. This scenario is not highly likely because the timing between cue onset and disk onset in all these experiments was too short for the voluntary allocation of sustained attention (e.g., Nakayama & Mackeben, 1989). Nevertheless, to ensure that any effects found reflect only the involvement of transient attention, the validity of the cue was reduced in this experiment to 50%, and the disks could appear in one of two possible locations. Specifically, on half of the trials—the *valid* trials—the attentional cue appeared above the disk location, and on the other half—the *invalid* trials—it appeared above the other location. Thus, the attentional cue in this experiment is no longer informative, and the observers have no incentive to voluntarily attend the cued location. If transient attention prolongs the perceived duration, even when no voluntary mechanisms are involved, the attentional effects on the perceived duration in the valid trials should resemble those of the previous experiments of this study.

The attentional cue in this experiment was an onset cue like the one used in Experiments 1 and 2. However, to ensure that an attentional prolongation effect does not merely reflect a local integration of the cue and disk, a different neutral cue was employed. This neutral cue was similar to the multibar cue employed successfully in Experiment 3 and in previous studies (Talgar et al., 2004; Yeshurun, 2004), but because there were only two possible locations, it was composed of two bars. Each of the bars was identical to the bar used as the attentional cue, ensuring that the local information surrounding the attended and neutral disks is identical.

If the prolonged perceived duration of the attended disk found in Experiments 1–3 is a consequence of the advanced attraction of attention by the onset of the cue rather than a mere local integration of the response to the cue and disk, and if transient attention prolongs the perceived duration, even when no voluntary mechanisms are involved, an attentional prolongation of the perceived duration should be found even when the attentional cue is no longer informative.

Method

Observers. Fifteen students from the University of Haifa participated in this experiment; none of them participated in the previous experiments. All of the observers were naive to the purpose of the study, and had normal or corrected to normal vision.

Stimuli, apparatus, and procedure. The stimuli, apparatus, and procedure were identical to Experiment 2 except for the following: The grey disks were presented in one of two possible locations at 5° of eccentricity. The attentional cue was identical to the onset cue employed in Experiment 2, but with 50% validity: On the valid trials (50% of the trials) it appeared above the disk's location, and on the invalid trials (50% of the trials) it appeared above the other location. The neutral cue was composed of two horizontal bars appearing above the two possible locations. Each bar was identical to the bar employed as the attentional cue. Each observer viewed 50 practice trials and 800 experimental trials presented in a randomized order.

Results and discussion

The PSEs for each observer and each possible duration of the neutral disk were estimated separately for the valid and invalid conditions. Then the various durations of the neutral disk were divided by their corresponding PSEs. As in Experiments 1–3, the average of the valid condition quotient was significantly higher than 1, $t(14) = 2.64$, $p < .01$ (Figure 6), and it did not vary significantly between the tasks (i.e., "report longer" vs. "report shorter"). Hence, an attentional prolongation of the perceived duration was found even when the cue was no longer informative. The quotient of the invalid condition did not differ significantly from 1.

Given that the time between cue onset and disk onset was shorter than the time typically needed for voluntary allocation of sustained attention, and given the fact that in this experiment there was no incentive for voluntary allocation of attention, we can conclude that the prolonged perceived duration of the attended disk is due to the operation of transient attention without the involvement of controlled attentional mechanisms.

GENERAL DISCUSSION

The four experiments of this study were designed to explore the effects of transient attention on the perceived duration of a brief visual event when transient attention is manipulated directly with peripheral precues (onset cue in Experiments 1, 2, and 4; singleton cue in Experiment 3), and the task of duration judgement is a single task employing simple stimuli to avoid undesired nontemporal processing. The results of all four experiments indicate that the allocation of transient attention to the target location leads to an overestimation of the target duration. This attentional prolongation of

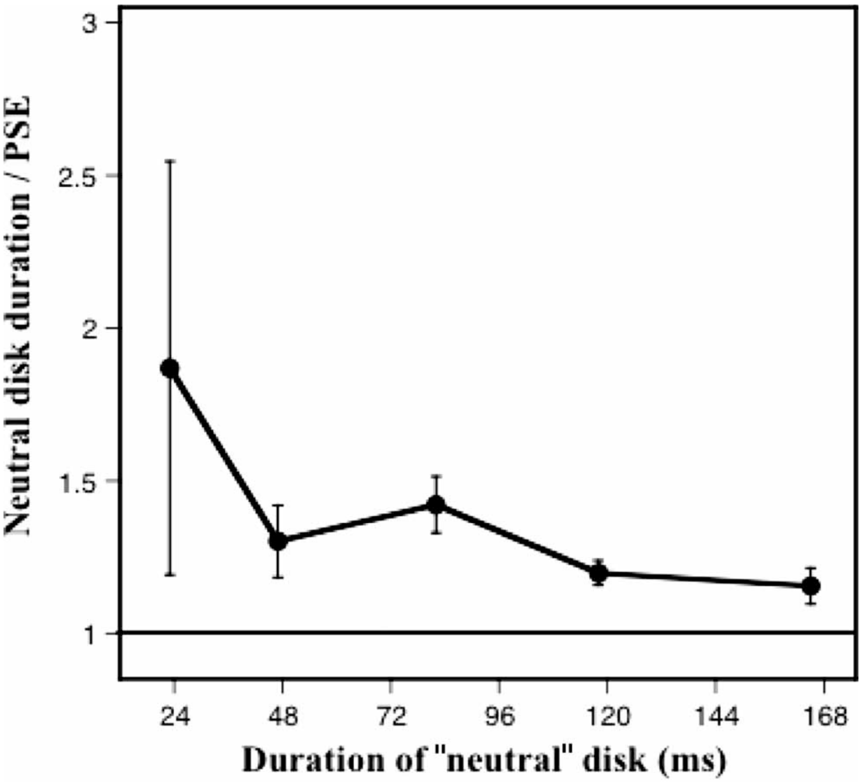

Figure 6. Experiment 4: The duration of the neutral disk in the valid condition divided by its estimated PSE as a function of the neutral disk duration. Error bars correspond to one standard error.

the perceived duration was found even with a singleton cue and a multibar neutral cue that ensured the results are not due to mere local interactions between the cue and the target, and even when the attentional cue was not informative (i.e., the target was equally likely to appear in a cued and a noncued location).

The finding that transient attention prolongs the perceived duration is consistent with several previous studies demonstrating that other components of visual attention prolong the perceived duration (e.g., Enns et al., 1999; Mattes & Ulrich, 1998; Tse et al., 2004; Ulrich et al., 2006). Tse et al. (2004) and Ulrich et al. (2006) manipulated the frequency at which stimuli are presented, and found that the less frequent stimuli (i.e., unexpected stimuli) are judged as longer than the frequent stimuli (i.e., expected stimuli). These studies interpret their findings in relation to the notion of a counter that counts the number of pulses generated by a hypothetical internal clock or the number of information units processed for a given event (e.g., Thomas

& Weaver, 1975; Treisman, 1963). According to this view of time perception, the perceived duration of an event is based on the number of pulses or units counted within the presentation of that event. Both studies attribute their findings to an increase in the number of pulses or units counted during an unexpected event, which results in a longer perceived duration of the unexpected event. Specifically, Tse et al. suggest that the unexpected stimuli capture attention, and that the allocation of attention boosts the processing of those attended stimuli. This results in counting more processed information units and therefore leads to the expansion of perceived duration. Ulrich et al. suggest that the novelty of the unexpected stimuli elevates the level of arousal, which in turn speeds up the internal pacemaker. Although these studies did not employ spatial attention, as all stimuli were presented at the centre of the screen, we can nevertheless consider their explanations as a possible account of our findings.

The explanation involving an increased rate of information processing due to attentional allocation (Tse et al., 2004) seems more relevant for complex displays, because when complex information is presented for a brief duration, it is likely that observers might not have enough time to process all the information that is present in the display. In such cases, an attentional increase of processing rate might indeed result in an increased amount of processed information, which might correspond to an increase in the number of processed information units. Our display, however, is very simple—a single disk of uniform, fixed luminance. It is quite likely that even with the shortest presentation of a neutral disk all the information present in the display is processed. An attentional increase of the processing rate would only result in an earlier termination of processing. Thus, if the only explanation for the attentional prolongation effects is an attentional increase of processing rate, we should not have found a prolongation effects with such simple stimuli, because for both attended and neutral disks the amount of information processed is equal. In fact, as suggested by Ulrich et al. (2006), because an attentional increase of processing rate with simple displays should lead to an earlier termination of processing, it predicts an opposite effect to the one found here. That is, because the processing of the attended stimulus takes less time its perceived duration should be shorter. The suggestion that the elevated level of arousal speeds up the internal pacemaker (Ulrich et al., 2006) is also not relevant for our current findings, especially those of Experiment 3 in which the attentional and neutral cues were highly similar, because there is no reason to believe such cues result in different levels of arousal. Moreover, as noted by Ulrich et al., when spatial cues are used to attract spatial attention, the attended stimulus is actually the expected stimulus as it appears at the expected location. Thus, elevated level of arousal due to the novelty of the stimulus could not account for our findings.

Studies that manipulated spatial attention are more closely related to this study (Enns et al., 1999; Mattes & Ulrich, 1998), although these studies employed spatial cues that direct sustained attention to the target location, whereas we used spatial cues that attract transient attention to the target location. Still, their findings are very similar to ours as these studies found that stimuli appearing at the cued location are judged as having a longer duration than stimuli appearing at a noncued location. Enns et al. (1999) interpreted their findings in the context of the reentrant pathway model (Di Lollo, Enns, Rensink, 2000) suggesting that attention is involved in the establishment of an iterative processing loop between higher brain centres and lower brain regions. When the target appears at the cued location (i.e., the expected location) there is a high level of agreement between the expectations generated by higher brain centres and the incoming sensory data. This agreement leads, via the iterative processing, to enhancement and prolongation of neural activity in a sensory register that was generated in response to information gathered at the attended location. Mattes and Ulrich (1998) suggest that attention prolongs the profile of the response function to the attended stimulus. Specifically, they suggest that the response function associated with the attended stimulus may have a steeper increase and a higher maximum level than the response function associated with unattended stimuli, resulting in a longer profile function for attended stimuli. Thus, both studies offer a similar explanation to account for the finding that spatial attention prolongs the perceived duration. Essentially, both suggest that the internal response generated for the attended stimulus is longer than the response generated for unattended stimuli. Evidently, this suggestion could be cooperated with the notion that the perceived duration of an event depends on the number of pulses counted by an internal counter before the response to the event decays. Because if the internal response to the attended event lasts longer, more pulses will be counted during the attended event and its duration will be perceived as longer.

Our current finding that the advanced allocation of transient attention to the stimulus location prolongs its perceived duration could also be accounted for by an attentional prolongation of the internal response to the attended stimulus. Moreover, this account of the attentional prolongation of the perceived duration is also consistent with other studies that explored the effects of transient attention on various aspects of temporal perception (Rolke, Ulrich, & Bausenhart, 2006; Yeshurun, 2004; Yeshurun & Levy, 2003). For instance, if the internal response is longer with transient attention the perceived termination of an attended stimulus should be delayed. Indeed, when observers were asked to respond as fast as possible to the offset of the target, their reaction times were longer when a peripheral cue attracted transient attention to the target location (Rolke et al., 2006). Similarly, if transient attention prolongs the internal response, it should impair the ability to resolve rapid changes in light intensity (i.e., degrade the temporal resolution). Indeed, observers' ability to detect a brief temporal gap occurring between two successive flashes was diminished when a peripheral cue allowed them to attend in advance to the flashes location (Rolke, Dinkelbach, Hein, & Ulrich, 2008; Yeshurun, 2004; Yeshurun & Levy, 2003), and when participants were asked to discriminate the temporal order of two spatially adjacent dots, their discrimination performance was impaired by an automatic orienting of attention to the dots location (Hein, Rolke, & Ulrich, 2006). These instances of attentional degradation in temporal resolution could be accounted for by an attentional mechanism that prolongs the internal response because longer internal responses to such brief successive stimuli increase the chance that these internal responses will be integrated over time into a single combined percept, which would impair the ability to detect the presence of a temporal gap occurring between those stimuli or the ability to determine which of the two stimuli appeared first. Thus, an attentional prolongation of the internal response is also consistent with the finding that under limited attentional resources the duration of visible persistence, and therefore the length of temporal integration, is shortened (Visser & Enns, 2001), although this study used the attentional-blink paradigm and did not directly manipulate spatial attention.

What is the neural mechanism that underlies this attentional prolongation of the internal response? We can only speculate. One possible implementation of an attentional mechanism that prolongs the internal response is a mechanism that favours parvocellular over magnocellular activity (Yeshurun, 2004; Yeshurun & Levy, 2003). Starting as early as the retina, visual cells are divided into two types—parvocellular and magnocellular. These two types of cells project to parallel neural systems in the LGN and the primary visual cortex (V1), and remain somewhat distinct even in their projection to higher visual cortical areas. Many studies (e.g., Derrington & Lennie, 1984; Maunsell, Nealey, & DePriest, 1990; Merigan & Maunsell, 1993; Schiller & Logothetis, 1990; Solomon, White, & Martin, 1999) have shown that parvocellular neurons have longer response duration, slower decay, longer temporal integration, and higher spatial resolution than magnocellular neurons. Magnocellular neurons have a higher temporal resolution than parvocellular neurons, but they are relatively colour-blind and a red diffused light inhibits their activity.

In view of these findings and evidence of attentional effects as early as V1 (e.g., Gandhi, Heeger, & Boynton, 1999), an attentional mechanism that facilitates parvocellular activity but inhibits magnocellular activity can account for the present finding and a range of attentional effects found previously. Specifically, because parvocellular neurons are typically active for a longer duration than magnocellular neurons and are characterized by a slower decay, an attentional facilitation of parvocellular activity at the attended location should result in a prolonged perceived duration of the attended stimulus, as we found in this study. Similarly, due to the prolonged activation of parvocellular neurons and their slower decay they also exhibit longer temporal integration. Hence, an attentional mechanism that facilitates parvocellular over magnocellular neurons can account for the findings that attention prolongs the duration of temporal integration (Visser & Enns, 2001). Furthermore, given the lower temporal resolution of parvocellular neurons, the hypothesis that transient attention favours parvocellular over magnocellular activity is also consistent with the findings that transient attention degrades the temporal resolution at the attended location (Hein et al., 2006; Rolke et al., 2008; Yeshurun, 2004; Yeshurun & Levy, 2003). This hypothesis is further supported by the findings that the attentional decrement in temporal resolution is greatly reduced when isoluminant stimuli or a red background are used (Yeshurun, 2004), because performance with isoluminant stimuli or a red background is primarily mediate by the parvocellular system, and therefore should not be greatly affected by any parvomagno inhibitory effects elicited by attention. Moreover, this hypothesis can also account for attentional effects on the spatial aspect of perception. In particular, directing transient attention to the target location improved performance in both acuity tasks—detection of a spatial gap with "Landolt-squares", and hyperacuity tasks—discrimination of offset-direction with Vernier targets (Yeshurun & Carrasco, 1999). In addition, the advanced allocation of transient attention to the location of a texture target enhanced the ability to segment it from the texture background when this target appeared at the periphery where the spatial resolution was too low, but impaired performance at the fovea where the spatial resolution was already too high (Yeshurun & Carrasco, 1998, 2000). These findings led to the conclusion that transient attention enhances spatial resolution, and given that parvocellular neurons have higher spatial resolution than magnocellular neurons the facilitation of parvocellular activity should indeed result in attentional enhancement of spatial resolution.

Although the current findings are clearly in line with the hypothesis that transient attention favours parvocellular over magnocellular activity they do not test it directly, and other suggested mechanisms of attention might also be able to account for our results. Still, to the best of our knowledge, this is the only attentional mechanism that can account for all the effects of attention we have described. Further research is required to test the viability of this hypothesis in general, its relevance to the attentional prolongation of the perceived duration, and whether other, possibly higher order, processes also underlie this prolongation effect.

To conclude, we have found that directing transient attention to the stimulus location prolongs the perceived duration of this attended stimulus, when compared to brief nonattend stimuli. Our findings regarding transient attention complement previous findings of similar prolongation effects with different components of visual attention, and they might be due to attentional prolongation of the internal response generated by information gathered at the attended location.

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