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Processing Demand Modulates the Effects of Spatial Attention on the Judged Duration of a Brief Stimulus

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Running head: ATTENTION AND DURATION JUDGMENT

Abstract

How does attention influence the judged duration of a brief stimulus? In the four experiments reported here, we show that the effect of spatial attention on duration judgment depended on the processing demand of the concurrent nontemporal task. When participants had to perform a speeded letter discrimination task in addition to duration rating, the judged duration was longer at a cued location than at an uncued location regardless of whether the cue was exogenous or endogenous. However, when the same stimuli were presented but no concurrent nontemporal task was required, duration was judged to be shorter at the cued location compared to uncued locations. Furthermore, while spatial attention influenced duration judgment, no object-based attentional effects were found. These findings suggest that although spatial attention plays an important role in the judged duration of a briefly presented stimulus, its effect is mediated by the processing demand of the task.

One of the central questions in vision research is how attention influences visual information processing. Numerous studies have shown that directing attention to a spatial location or an object increases the speed and/or accuracy of processing stimuli there relative to elsewhere (e.g., Baylis & Driver, 1993; Chen, 1998a, 2000a; Duncan, 1984; Egly, River, & Rafal, 1994; Hoffman & Nelson, 1981; Posner, Snyder, & Davidson, 1980; Shaw & Shaw, 1977). Furthermore, attention reduces response variability (e.g., Prinzmetal, Amiri, Allen, & Edwards, 1998; Prinzmetal & Wilson, 1997) and enhances signal to noise ratio of a briefly presented stimulus (e.g., Bashinski & Bacharach, 1980; Downing, 1988). These effects suggest that attention acts to enhance visual information processing.

However, recent studies suggest that the effect of attention on visual information processing may be more varied than had been previously appreciated. For example, Yeshurun and Carrasco (1998) show that whereas attention facilitates texture segregation at peripheral locations, it impairs it at central locations. Chen (2000b) reports that although spatial attention reduces response interference from incompatible distractors when target selection does not require a narrow attentional window, the effect is abolished when the task is made more difficult so that a narrow attentional window is needed to complete the task. Furthermore, allocating attention to an incompatible color word (e.g., the word RED written in green ink, and the task is to identify the color of the ink as quickly as possible) increases the Stroop interference effect (Stroop, 1935) rather than reduces it (Chen 2000c). These findings indicate that how attention influences visual information processing may depend on such factors as the nature of the task and the spread of attention during task completion.

In addition to the factors mentioned above, the efficiency of selective attention appears to be modulated by the perceptual load involved in the processing of the target. Lavie and her colleagues (e.g., Lavie, 1995; 2000; Lavie & Cox, 1997; Lavie & Tsal, 1994) propose that high perceptual load for a task is a necessary requirement for efficient selective attention, and that perception proceeds automatically to the extent of available resources. When the processing of relevant task information does not consume all available resources (described as a "low-load" condition), the processing of task-irrelevant information will continue until all resources are used, and this will lead to high distractor interference. In contrast, when the processing load of the relevant task is high (the "high-load" condition), no spare resources are available to process the task-irrelevant information. Hence, little distractor interference occurs. For example, in one experiment, Lavie and Cox asked participants to search for a target letter displayed simultaneously with a compatible, a neutral, or an incompatible irrelevant letter in the periphery. Compared to the neutral letter, participants suffered more interference from the incompatible letter when the rest of the items in the display consisted of homogeneous distractors such as Os (the low-load condition) rather than heterogeneous distractors such as H, W, M, Z, or K, etc. (the high-load condition). Therefore, attention may facilitate task performance, may interfere with task performance, and the efficiency of selective attention is moderated by the processing demands of the task.

To date, most students of attention focus on how attention influences the appearance of, or the responses to, visual stimuli. Only a few researchers have directly examined the effects of attention on the processing of temporal characteristics of a briefly presented stimulus, and the main finding is that spatial attention directed to a stimulus prolongs the judged duration of that stimulus (e.g., Enns, Brehaut, & Shore, 1999; Mattes & Ulrich, 1998). In a recent study, Mattes and Ulrich used precues to manipulate attention explicitly. They showed participants a briefly presented black dot for one of two intervals after an informative endogenous precue, and the cue validity was varied across blocks. The task was to categorize the stimulus duration as short, medium, or long. Among other important findings, the result most relevant to the current study is that observers' judged duration increased with stimulus probability. Similar results were also obtained in a subsequent dual task experiment, in which observers compared the stimulus duration of a target dot at either a cued or an uncued location with the stimulus duration of a previously presented comparison dot at fixation. Before the duration judgment task, observers had to perform a speeded dot detection task. Again, the stimulus duration was judged to be longer at the cued location compared to the uncued location. At first glance, these results appear to suggest that attention increases the judged duration of a brief stimulus regardless of the nature and the processing demand of a task. However, processing demand was not the primary focus of the study and many methodological differences existed between these two experiments. Given this, it was difficult to determine whether processing demand could modulate the effect of attention on duration judgment.

In the series of experiments reported here, we explored the role of processing demand in modulating the effect of attention on duration judgments. We did so by asking participants to perform either single or dual tasks while presenting them with identical stimulus displays. Experiment 1 employed a dual-task paradigm. Observers performed a letter discrimination task as a primary task, and a duration rating task as a secondary task. We used an exogenous cue, and manipulated observers' allocation of both space- and object-based attention. Although object-based attention has been found in a variety of studies using reaction time and/or accuracy as dependent measures (e.g., Baylis & Driver, 1993, Chen, 1998a; 2000a; Duncan, 1984; Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998), the question of whether object-based attention could also influence duration judgment has not been addressed before. In Experiment 2, we investigated whether the attentional effect found in Experiment 1 was modulated by the presence of a concurrent, high processing demand, nontemporal second task. Observers performed the same duration rating task without letter discrimination. Experiments 3 and 4 generalized the results of the first two experiments with endogenous cues to confirm that the results were not due to other factors such as misattribution or forwarding masking.

Experiment 1

Experiment 1 investigates the role of attention in the duration judgment of a brief stimulus by using an exogenous cue in a dual task paradigm. Stimulus displays were made up of two rectangles, either vertically or horizontally aligned as shown in Figure 1. After a precue at one of the four end locations of the rectangles, an X or an O appeared either at the cued location or at an uncued location for one of three duration. The participants performed a speeded letter discrimination task, followed by duration rating of the target stimulus. Of particular interest was the participants' judged duration as a function of the cue-target relationship.

Method

Participants. Thirty undergraduate students from the University of Mississippi participated in the study to satisfy course requirements of the psychology department. All reported to have normal color vision.

Apparatus and Stimuli. A Power Macintosh 6100/66 computer with a 13-inch RGB monitor was used to present stimuli and to record responses. Participants viewed the monitor from a distance of approximately 60 cm in a dim room. A commercially available graphic program (Superpaint 3.0) and experimental program (MacProbe 1.6.9) were used to generate and display stimuli, and to record responses.

The stimulus display consisted of two white outlined rectangles against a homogeneous black background. The rectangles were either horizontally or vertically aligned. At a viewing distance of approximately 60 cm, each rectangle subtended 10.2° of visual angle in length and 1.8° in width. With a separation of 6.6° between the inner contours of the rectangles, the entire stimulus display subtended 10.2° in both length and width. The stimulus display was presented either alone, or with one of three other stimuli: A fixation cross, a cue, or a letter. Both the fixation cross and the cue were white, and the letter was green. The fixation was placed at the center of the display, and it subtended 0.95° of visual angle. The two letters used in the experiment were uppercase X and O (font = Geneva; size = 48), each has a radius of about 0.7°. Each trial contained only one letter, which was always presented against a small red square subtending 1.6° of visual angle. The cue subtended 1.8° of visual angle in both length and width.

Design and Procedure. The experiment used a repeated measures design. The variables of interest were stimulus duration (short, medium, and long) and the location of the target relative to the cue (same-object-same-location, same-object-different-location, different-object-near-location, and different-object-far-location). Altogether there were 12 experimental conditions, with each duration having four cue-target locations: same-object-same-location (SS), when the target appeared in the cued location; same-object-different-location (SD), when the cue and the target were in the same rectangle but different locations;

different-object-near-location (DN), when the cue and the target were in different objects and the target was in the near end of the other rectangle from the cue; and different-object-far-location (DF), when the cue and the target were in different objects and the target was in the far end of the other rectangle from the cue.

Insert Figure 1 about here

Each trial started with the presentation of the fixation cross together with either two horizontal or vertical rectangles for 1005 ms. The stimulus display was presented at the center of the screen, with the fixation cross at the center of the display. Upon the offset of the fixation (the rectangles remained on the screen throughout the trial), the cue was flashed for 45 ms at one of the four ends of the rectangles. After the termination of the cue, the rectangles remained on the screen for another 45 ms before a target letter appeared. The letter could either be an X or an O, and it appeared at one of the four end regions of the rectangles randomly with equal probability. Please note that the spatial separation between the cue and the target was identical in SD and DN conditions, both subtending 8.30° of visual angle. The duration of the letter varied from trial to trial: 60 ms, 105 ms, or 150 ms. Upon the offset of the letter, the screen returned to its background black color until the participant responded. The participant was told to identify the target letter as quickly as possible. They used their right index and middle fingers to press one of the two labeled keys on the keyboard (the "<" key for X, and the ">" key for O). Upon response, a sentence would appear on the screen, asking the participants to rate the duration of the letter, 1=short, 2=medium, and 3=long. They were then required to use their left hands to do the duration task. Three fingers (i.e., the ring, middle, and index fingers) were used to press the Z, X, and C keys, which were labeled 1, 2, and 3, respectively. The sentence remained on the screen until response. No feedback was provided during the experiment, and the inter-trial interval was 1.5 s.

The participants were aware that the cue was not informative. The importance of maintaining fixation throughout the trial was emphasized. The letter discrimination task was characterized as a primary task, and both speed and accuracy were stressed. The duration categorization was described as a secondary task, and only accuracy was emphasized. Before the experiment started, participants were shown examples of trials, four trials with short intervals first, followed by four trials with medium and long intervals. No letter discrimination was required at this stage. If participants indicated that they could see differences in duration between these trials, they were allowed to proceed to the next practice session. Otherwise, the whole process was repeated. Most participants were able to accomplish this after two repetitions. Participants then completed a block of 30 trials in which both speeded letter discrimination and duration rating were required. The experiment session consisted of 3 blocks of 192 trials, with half of them containing an "X", and the other half an "O". Each letter occurred at one of the four end regions of the rectangles equally often, and there were as many *long interval* trials as there were *medium interval* and *short interval* ones. This resulted in 48 trials per condition for each participant. The total experiment took about 45 to 50 minutes to complete, and the observers were encouraged to take short breaks between the blocks.

Results and Discussion

Letter Discrimination Task. The reaction time and accuracy data are shown in Table 1. Repeated measures analysis of variance (ANOVA) on reaction time showed a significant main effect for cue, $F(3, 87) = 77.94$, $p < .001$, with no main effect for duration, $F(2, 58) < 1$, or duration by cue interaction, $F(6, 174) = 1.26$, $p > .2$. Planned mean comparisons revealed faster reaction time to targets at the cued location (SS = 457 ms) than at any of the uncued locations (SD = 487 ms, DN = 494 ms, and DF = 492 ms. $t(29) = 8.41$, $p < .001$, for comparison between SS and SD; $t(29) = 12.47$, $p < .001$, for comparison between SS and DN; and $t(29) = 16.68$, $p < .001$, for comparison between SS and DF). In addition to these findings, participants were also faster in SD than DN conditions, $t(29) = 2.50$, $p < .02$. The difference between SD and DF conditions approached significance, $t(29) = 1.98$, $p < .06$. ANOVA on the accuracy data found no main effects or interaction, suggesting no speed-accuracy trade-off between reaction time and accuracy.

Insert Table 1 about here

Like previous studies in the field (e.g., Chen, 1998a; Egly et al., 1994; Moore et al., 1998), we found both a location effect and an object effect. The location effect was demonstrated by the faster reaction times to targets in a cued location than in an uncued location, and the object effect was indicated by the faster reaction times to targets in the uncued location of the same object compared to a different object. These reaction time data suggested that our manipulation of attention was effective.

Duration Categorization Task. The duration data are shown in Table 2. ANOVA revealed significant main effects for both duration, $F(2, 58) = 62.78$, p < .001, and cue, $F(3, 87) = 4.23$, p < .01, but no significant interaction between the two, $F(6, 174) = 1.15$, p > .3. Planned mean comparisons on duration showed that participants could discriminate between different presentation duration, and that they judged the duration of the stimulus to be longer when it was long (mean rating = 2.13) relative to when it was medium (mean rating = 1.88, $t(29) = 7.19$, p < .001), or short (mean rating = 1.62, $t(29) = 8.18$, p < .001). The difference between the medium and short duration conditions also reached significance, $t(29) = 7.73$, p < .001. Because similar duration effects are found in all four experiments reported here, we will not provide detailed statistical information in later experiments. More importantly, the judged duration of the stimulus was affected by the manipulation of attention. Participants rated the stimulus interval to be longer in the cued location (mean rating = 1.99) than in an uncued location (mean rating = 1.84). Specifically, the stimulus in SS conditions was perceived to be longer than the same stimulus in DF conditions (mean rating = 1.81, $t(29) = 2.24$, p < .02), or in DN conditions (mean rating = 1. 84, $t(29) = 2.06$, p < .05). The difference between SS and SD conditions (mean rating for SD = 1.86) approached significance, $t(29) = 1.79$, p < .09. A significant difference was also found between SD and DF conditions, $t(29) = 2.91$, $p < .001$, although the difference between SD and DN conditions did not reach significance, $t(29) = 1.56$. $p > .1$.

Insert Table 2 about here

Our duration data show that spatial attention increased the judged duration of a brief stimulus in the current paradigm. When participants had to perform a speeded letter discrimination task in addition to duration rating, the stimulus duration appeared to be longer at the cued location than at uncued locations, despite the fact that the cue was uninformative.

Although a significant object effect was indicated in reaction time, no object effect was found in duration rating. The lack of an object effect in duration judgment was not totally unexpected. Many reaction time studies, including letter discrimination tasks similar to that employed in the present experiment, have shown that an object effect is typically much smaller than a location effect (e.g., Chen, 1998a; Egly et al., 1994; Moore et al., 1998). Furthermore, an object effect seems to be sensitive to a number of factors that do not necessarily influence a location effect. For example, the object effect depends on the perceptual organization of a stimulus (Chen, 1998a), the size of the attended region (Lavie & Driver, 1996, but see Lamy, in press), the uniform connectedness of an object's surface (Kramer & Watson, 1995), and the type of precue employed in the study (Arrington & Dagenbach, 2000; Macquistan, 1997; Neely & Dagenbach, 1996, but see Abrams & Law, 2000). Given these characteristics, it is possible that duration rating might not be a sensitive enough measure for the manifestation of an object effect.

Our next question is whether the attentional effect on duration judgment would remain the same when participants need not perform the letter discrimination task. We tested this possibility by showing participants identical stimulus displays as those of Experiment 1, but asked them to perform only the duration rating task.

Experiment 2

Methods

Participants. Twenty-six new undergraduates from the same participant pool as before took part in the study. All had normal or corrected to normal vision and color vision. None knew the purpose of the experiment in advance.

Apparatus and stimuli. Both the apparatus and stimuli were exactly the same as Experiment 1.

Design and Procedure. The design and procedure were identical to those of Experiment 1 with the exception that no letter discrimination was required of the participants. Upon the offset of the target display that contained either an X or an O, participants rated the duration of the letter regardless of which one they saw. Only accuracy was stressed.

As before, the experiment consisted of 3 blocks of 192 experimental trials, and it took approximately 40 minutes to finish.

Results and Discussion

The duration data are shown in Table 3. Participants showed significant main effects of duration, $F(2, 50) = 55.27$, $p < .001$, cue, $F(2, 50) = 3.94$, $p < .02$, and duration by cue interaction, $F(6, 150) = 2.92$, $p < .02$. Like Experiment 1, they could discriminate the three types of duration (the mean ratings for the long, medium, and short duration are 2.15, 1.91, and 1.68, respectively). However, in contrast to the previous experiment, they judged the stimulus duration to be shorter at the cued location relative to an uncued location (the mean ratings for the SS, SD, DN, and DF conditions were 1.75, 1.97, 1.97, and 1.98, respectively). As for the duration by cue interaction, single factor repeated measures ANOVA reveal that for trials having long and medium duration intervals, a significant effect for cue was found, $F(3, 75) = 6.02$, p <

.002, and $F(3, 75) = 3.25$, $p < .03$, respectively. For trials with long duration, planned mean comparison showed shorter duration judgment when the stimulus was at a cued location than when it was at an uncued location, $t(25) = 2.42$, $p < .03$ for comparison between DF and SS, $t(25) = 2.12$, $p < .05$ for comparison between DN and SS, and $t(25) = 2.66$, $p < .02$, for comparison between SD and SS. For trials with medium duration, the comparison between DF and SS, and DN and SS approached significance, $t(25) = 1.98$, $p < .06$, and $t(25) = 1.96$, $p < .07$, respectively. ANOVA did not reveal any reliable differences among conditions for trials with short duration, $F(3, 75) = 1.53$, $p > .2$. Given the data, it appears that in the present paradigm attention affected duration judgment only when the presentation duration was relatively long.

Insert Table 3 about here

The results of Experiment 2 suggest that at least in the current paradigm the presence or absence of a concurrent nontemporal task plays an important role in determining the direction of the attentional influence on the judged duration of a briefly presented stimulus. When participants had to engage in a speeded letter discrimination task in addition to duration estimation, spatial attention prolonged the stimulus duration. In contrast, in the absence of a concurrent nontemporal task, spatial attention shortened judged duration.

Why is our result different from those of Mattes and Ulrich (1998), who reported increased stimulus duration at the cued location even when duration judgment was the sole task? The many methodological differences between Mattes and Ulrich's experiment and ours make it difficult to isolate the reason for the different results. One difference that readily comes to mind is the stimulus onset asynchrony (SOA) between the cue and the target. In our experiments, the cue-target SOA was 90 ms, whereas in Mattes and Ulrich, it was 2000 ms. Although longer SOA could allow participants to make eye movements, the fact that similar results were obtained when the authors monitored participants' eye movements makes it unlikely for SOA to be a contributing factor. Another difference between the two experiments is the specific stimuli used in the studies. Whereas we employed letters (X vs. O), Mattes and Ulrich chose dots. It is possible that because the task load was low, and letters are inherently more meaningful than dots, participants in our experiments may have been processing some aspects of the stimuli even though letter discrimination was not required. This, however, does not mean that participants processed the letters in the same way as they did in

Experiment 1. After all, whereas letter identification was the primary task in Experiment 1, no identification was needed in Experiment 2. Similar differences may underlie our experiments and those of Enns et al. (1999), who used dot stimuli in a different paradigm and found longer judged duration at the cued than uncued locations without a concurrent nontemporal task. Task load may have interacted with stimulus type in some way, leading to the observed differences among the various studies. At present, we are still unclear as to the nature of the interaction.

Even though the results of Experiments 1 and 2 demonstrated the importance of processing demand in the attentional effect on duration judgment, one might argue that there are confounds in our experiments. For example, participants could have misattributed the exogenous cue as part of the target stimulus in the valid cue condition, leading to longer judged duration on valid than invalid cue trials in Experiment 1 (see Witherspoon and Allen, 1985, for a related phenomenon concerning judged duration and stimulus familiarity). These cues could also have induced forward masking effects that might have influenced duration judgment. Furthermore, because of the brief stimulus presentation duration and the short SOA between the cue and the target, participants might experience apparent motion on invalid trials but not on valid trials, resulting in longer judged duration on invalid than valid trials in Experiment 2. Even though none of these factors can adequately explain why we obtained the opposite pattern of results when identical stimulus displays were used in both experiments, nonetheless, it is important to see if a similar pattern of results will be obtained when endogenous cues are used. Endogenous cues should minimize these factors.

Experiment 3

Methods

Participants. Nineteen new participants were recruited from the same undergraduate participant pool at the University of Mississippi.

Apparatus and Stimuli. The apparatus remained the same as before. Several changes were made to the stimuli. First, to minimize the effect of visible persistence (Breitmeyer, 1984), all the stimuli including the outline rectangles, the letters, and the precue were changed from white to black, and they were presented against a white background. Second, rather than an exogenous luminance cue, the new experiment employed an endogenous arrow cue. It subtended 2.96^0 of visual angle, and was located at the center of the display. Third, the small red square against which the target letter was displayed in Experiments 1 and 2 was no longer used in this experiment. All other aspects of the stimuli were identical to those employed in the first two experiments.

Design and Procedure. The only changes regarding the design of the experiment concerned the cue validity and the number of experimental conditions. To encourage participants to attend to the cue, valid cue trials comprised 60 percent of the total trials (the SS condition), with the remaining 40 percent of trials divided equally between the same-object-different-location condition (SD) and the different-object-near-location condition (DN). The different-object-far-location condition (DF) was not included in the experiment. With three levels of stimulus intervals (i.e., short, medium, and long), there were 9 conditions altogether.

The experimental procedure was similar to Experiment 1. Each trial started with the presentation of a fixation cross together with either two horizontal or vertical rectangles, and the rectangles remained throughout the trial. The fixation cross stayed on the screen for 1005 ms, and 1005 ms after its offset, the cue appeared for 45 ms. After an SOA of 90 ms, the target letter was displayed for one of three intervals: 60 ms., 105 ms., or 150 ms.. As in Experiment 1, participants made a two alternative speeded response to the target letter before they rated its duration. The experiment comprised of 4 blocks of 120 trials, with 288 trials in the SS conditions, and 96 trials each in the SD and DN conditions.

Results and Discussion

The data for the letter discrimination task are shown in Table 4, and the duration ratings are in Table 5. Eighteen of the 19 participants' data were included in the analyses due to the excessively long reaction times of one participant whose mean response latencies were more than 3 standard deviations above the group mean.

Letter Discrimination Task. As expected, ANOVA found a significant main effect of cue, $F(2, 34) = 4.81$, $p<.05$, with no main effect of duration, $F(2, 34) < 1$, or duration by cue interaction, $F(4, 68) < 1$. Like Experiment 1, participants were faster to do the letter discrimination task when the target letter occurred at the cued location (RT = 519 ms) than at an uncued location (RT = 536 ms and 541 ms for SD and DN conditions, respectively), $t(17) = 2.17$, $p<.05$, for comparison between SS and SD conditions, and $t(17) = 3.20$, $p<.01$, for comparison between SS and DN conditions. Paired comparison between the SD and DN conditions did not reach significance, $t(17) < 1$.

Insert Table 4 about here

The lack of an object effect in the reaction time data in this experiment is consistent with prior reports in the literature. It is possible that different mechanisms are involved in different types of cues (Briand & Klein, 1987; Jonides, 1981; Nakayama & Mackeben, 1989). Therefore, while an object effect occurs with exogenous cues, it did not, in the present experiment, occur with endogenous cues, a result consistent with previous work (e.g., Arrington & Dagenbach, 2000; Neely & Dagenbach, 1996; Macquistan, 1997; but see Abrams & Law, 2000).

Duration Categorization Task. There were significant main effects for duration, $F(2, 34) = 42.61$, $p<.001$, and for cue, $F(2, 34) = 4.09$, $p<.05$, with no duration by cue interaction, $F(4, 68) < 1$. Like Experiment 1, participants could readily discriminate the three types of duration (the mean ratings for the long, medium, and short duration are 2.19, 1.91, and 1.58, respectively, and all pair-wise comparisons were significant). They also judged the stimulus interval to be longer at the cued location (1.94) compared to either of the uncued locations (1.88 for the SD condition, $t(17) = 2.11$, $p<.05$; and 1.86 for the DN condition, $t(17) = 3.0$, $p<.01$).

Insert Table 5 about here

Changing from exogenous to endogenous cues reduced the likelihood that the attentional effects observed in Experiment 1 were contaminated by such factors as precue misattribution or induced forward masking. Given that duration was judged to be longer at the cued location than at uncued locations regardless of cue type, we were reasonably confident that spatial attention increased the judged duration of a brief stimulus when participants had to perform a speeded nontemporal task in addition to duration estimation.

Experiment 4

This experiment examined whether the reversed effect of attention on duration perception observed in Experiments 1 and 2 was due to the effect of apparent motion on invalid trials. Participants were shown displays identical to Experiment 3, and they performed the duration rating task without engaging in letter identification. Since the experiment contained centrally located arrow cues, the effect of apparent motion, if any, should exert similar influence on both the valid and invalid trials. Therefore, if the results of Experiment 2 were primarily due to apparent motion, we should not find any cueing effects. However, if the results of Experiment 2 could be attributed to our manipulation in processing demand, we should still be able to observe longer judged duration on invalid than valid trials.

Methods

Participants. Twenty-five undergraduates from the same participant pool as before took part in the study to satisfy a course requirement. None had taken part in the earlier three experiments.

Apparatus and Stimuli. They were the same as those used in Experiment 3.

Design and Procedure. Other than the removal of the letter discrimination task, all other aspects of the experiments were identical to those of Experiment 3.

Results and Discussion

Table 6 contains the participants' data. One person did not complete the experiment, so the analyses were based on the remaining 24 people. ANOVA indicated significant main effects for both duration, $F(2, 46) = 27.23$, $p<.001$, and cue, $F(2, 46) = 3.49$, $p<.05$, with no duration by cue interaction, $F(4, 92) < 1$. As before, participants could distinguish the three levels of stimulus duration (the mean ratings for the long, medium, and short intervals were 2.16, 1.96, and 1.70, respectively), and all pair-wise comparisons reached significance. More interestingly, as in Experiment 2, participants rated the stimulus interval to be shorter at the cued location than at an uncued location (the mean rating for the SS, SD, and DN conditions were 1.92, 1.93, and 1.97, respectively). Paired comparison indicated a significant difference between the SS and DN conditions, $t(23) = 2.29$, $p<.05$. No other effects reached significance.

Insert Table 6 about here

The results of this experiment replicated those of Experiment 2, although the attentional effect was much smaller, and was only significant between the SS and DN conditions. It is worth noting that a reduction in the magnitude of the attention effect was also found from Experiment 1 to Experiment 3 when dual tasks were employed. Because an exogenous cue reaches the peak of its effect much more rapidly than an endogenous cue (Nakayama & Mackeben, 1989), the cueing effect might not have been fully realized in the last two experiments since SOAs were extremely short. However, despite reduced magnitude, the important thing is that the processing demand of a task has been found to mediate the effects of attention on duration judgment using both exogenous and endogenous cues.

General Discussion

Prior research has shown that in prospective duration estimation, when attention is manipulated through an endogenous precue (Enns et al., 1999; Mattes & Ulrich, 1998), observers' judged duration is increased at the cued location compared to an uncued location. Using both exogenous and endogenous cues, we extended these previous findings in several ways. We provided converging evidence that a briefly presented stimulus at an attended region could be judged longer than a stimulus at an unattended region regardless of cueing type. More importantly, we found that the effects of attention depended on the processing demand of a task. In dual tasks when processing demand was high, increasing attention increased judged duration (Experiments 1 and 3). In contrast, in single tasks when processing demand was low, increasing attention shortened judged duration (Experiments 2 and 4). Furthermore, duration judgments were not affected by object-based attention in our paradigms.

How can we account for the data? We believe that as the level of processing demands can modulate the efficiency of selective attention (Lavie, 1995, 2000), it can also modulate the effect of attention on duration judgment in our experiments. Experiments 1 and 3 involved high processing load.

According to Thomas and Weaver (1975), each stimulus is analyzed by two processors: a nontemporal information processor to encode the nontemporal features of a stimulus, and a timer to code the temporal information and to accumulate pulses that correlate positively with the passage of time. Due to limitations in our cognitive resources, attention has to be shared between these two processors. When more attention is devoted to one processor, less attention is available for the other. Insufficient attention could cause the loss of some pulses, leading to shorter judged duration. In our experiments, because participants had to switch attention from the cued to the uncued location on invalid trials, some pulses could be lost, resulting in the shorter judged duration at an unattended location relative to an attended location.

Alternatively, attention could influence duration perception via its effect on the perceptual quality of the target stimulus. Since letter discrimination was the primary task, participants might not have sufficient resources available to process the temporal cues of a stimulus duration, e.g., the onset/offset time of the target stimulus. Instead, they might infer the duration of a stimulus based on its brightness or clarity. From prior research, we know that attention can make a brief stimulus appear brighter (e.g., Bashinski & Bacharach, 1980; Downing, 1988), which in turn could make the stimulus interval appear longer

(Goldstone, Lhamon, & Sechzer, 1978) and the letter discrimination task easier. These effects were likely to result in longer judged duration at the cued location than at an uncued location. Although we can not distinguish between these two interpretations in our experiments, we lean towards the second interpretation because of the data pattern of Experiments 2 and 4. It is unclear how Thomas and Weaver's (1975) model would explain the shorter judged-duration at the cued location compared to the uncued location.

Assuming that the perceptual quality hypothesis is true, can we say that the effect we found in Experiments 1 and 3 is not an effect of attention but rather an effect of misattribution, i.e., participants mistakenly attributing the clearer or brighter stimulus as having a longer duration? Although this question is legitimate, we believe it is more accurate to attribute the differential duration ratings to our attentional manipulation because we used physically identical stimulus displays on both valid and invalid trials. Whatever effect the perceptual quality of the letters had on the participants was not due to the manipulation of the perceptual quality, but rather the manipulation of attention. In other words, differential perceptual quality of the letters is only a byproduct of attention. It is the distribution of attention that influenced the perceptual quality of the stimulus letters, which in turn affected the perception of the stimulus duration.

In contrast to Experiments 1 and 3, participants judged the stimulus duration to be shorter at the cued location compared to the uncued location. How can we explain that? One possibility is that the reversed data pattern is caused by differences in task priority among the experiments. Whereas duration rating was a secondary task in Experiments 1 and 3, it was a primary task in Experiments 2 and 4. There is evidence that duration judgment is influenced by task priority. Zakay (1998) showed that duration estimation was longer when it was a primary task than when it was a secondary task, and this priority effect was independent of the task complexity effect which he also manipulated in the study. In our experiments, the overall rating of the stimulus interval was also numerically higher in Experiments 2 and 4 (1.92 and 1.94, respectively) when duration rating was a primary task than in Experiments 1 and 3 (1.88, and 1.89, respectively) when it was a secondary task, even though the difference is not statistically significant, $F(1, 54) = 1$ for comparison between Experiments 1 and 2, and $F(1, 40) = 1.13$, $p<.20$ for comparison between Experiments 3 and 4). Although we can not determine from the present experiments whether the difference in task priority was a major contributor to our results, such an explanation does not seem likely. If task priority interacted with resource allocation, Zakay (1998) would have found a significant interaction between task priority and task complexity. Furthermore, in an experiment not reported here, we replaced the high demanding letter discrimination task of Experiment 1 with a less demanding letter detection task, and still asked participants to do the duration rating as a secondary task. We found that the attentional effect on duration judgment varied with the processing demand.

Another possibility is to attribute the reversal of the data pattern from Experiments 1 and 3 to Experiments 2 and 4 to the differential level of processing load required in the experiments. Experiments 2 and 4 involved low processing load, since participants were only asked to determine the presentation duration of the stimulus. Because letter identification was not needed, participants might be affected less by the clarity of the letter, but more by such temporal cues as the onset/offset time of the target stimulus. Spatial attention is known to speed up the detection of both stimulus onset (Chen, 1998b; Hikosaka, Miyauchi, & Shimojo, 1993a; 1993b; Stelmach & Herdman, 1991; Stelmach, Herdman, & McNeil, 1994) and stimulus offset (Downing & Treisman, 1997). In other words, to an observer, a stimulus could appear later as well as extinguish later on an invalid cued trial compared to a valid cued trial. If participants put more weight on their impressions of the offset time of a stimulus more than its onset time when they performed the task, this would bias their duration judgments in the direction of invalid cued trials, leading to longer judged duration on those trials compared to valid cued trials. Currently, it is still unclear under what conditions participants would be influenced more by the onset of a stimulus rather than the offset of a stimulus or vice versa. Further experiments are needed to understand the interactions among attention, processing demand and the judged duration of a briefly presented stimulus.

Our results are also related to the findings in the time perception literature, which show that temporal judgment is affected not only by the actual duration of an interval, but also by a variety of nontemporal factors (e.g., Hicks, Miller, & Kinsbourne, 1976; Predebon, 1996a). In prospective timing where observers are aware of the duration judgment task before the judged-interval starts, duration is judged to be longer when the to-be-judged interval is filled with complex stimuli than when it is not. For example, relative to an empty interval, observers report longer duration when the same interval is filled with words (e.g., Thomas & Weaver, 1975), light (e.g., Goldfarb & Goldstone, 1963), or tones (e.g., Buffardi, 1971; Ihle & Wilsoncroft, 1983). Similarly, an interval containing more stimulus events tends to be experienced longer than the same interval containing fewer stimulus events (e.g., Buffardi, 1971; Mo, 1971, 1974, 1975), and the effect has been observed in visual, auditory, and tactile modalities (e.g., Buffardi, 1971). Intervals containing moving stimuli are also perceived to be longer than the same interval containing stationary stimuli, and the same holds true for intervals filled with flickering light rather than those filled with static light (e.g., Lhamon & Goldstone, 1975).

In contrast, when participants have to engage in a concurrent nontemporal task in addition to duration estimation, the pattern of results reverses. The more complex the stimuli are, or the more difficult the nontemporal task is, the shorter the judged duration (e.g., Brown, 1985; Hicks et al., 1976; Hicks, Miller, Gaes, & Bierman, 1977; Macar, 1996; McClain, 1983; Predebon, 1996a, 1996b; Zakay, 1993, 1998). For instance, when participants were asked to sort cards into one stack, two stacks (by color), or four stacks (by suit) during a 42-sec interval, their judged duration decreased linearly from the one-stack condition to the four-stack condition even though task duration remained constant for all three conditions (Hicks et al., 1976, 1977). Similarly, negative correlation has been reported between judged duration of an interval and the number of words to be classified (e.g., Predebon, 1996a, 1996b), the number of angles to be identified (e.g., Zakay, 1993), and the level of difficulty in a line-tracing task (e.g., Brown, 1985). Although it is difficult to directly compare our results with the findings from the timing literature due to many methodological differences, these data do suggest that the presence or absence of a secondary nontemporal task influence duration judgment.

To summarize, the present study supports the notion that attention plays an important role in duration judgment. However, how it affects the judged interval of a briefly presented stimulus depends on the processing demand in completing a task.

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Table 1

Mean reaction times (in ms) and error rates (percent incorrect) for the letter discrimination task of Experiment 1. The standard deviations are presented in the parentheses.

	Conditions			
Duration	DF	DN	SD	SS
	Reaction Times			
Long	487 (74)	494 (79)	491 (81)	457 (73)
Medium	493 (74)	493 (76)	484 (78)	457 (77)
Short	497 (78)	494 (69)	487 (75)	455 (74)
Mean Overall	492 (74)	494 (73)	487 (76)	457 (73)
	Error Rates			
Long	9.4 (8.3)	7.2 (7.2)	7.6 (6.9)	6.8 (7.3)
Medium	7.1 (6.0)	6.8 (5.6)	7.6 (6.0)	8.4 (7.8)
Short	7.0 (5.3)	7.3 (6.2)	7.2 (8.4)	7.6 (5.9)
Mean Overall	7.8 (5.9)	7.1 (5.5)	7.5 (6.5)	7.6 (6.3)

Note. The notations for the conditions are: SS, same-object-same-location; SD, same-object-different-location; DN, different-object-near-location; DF, different-object-far-location. Please note that the standard deviations shown here represent the between-participant variability within a condition instead of the within-participant variability across conditions that is of interest in the present paper.

Table 2

Mean perceived duration for the duration categorization task of Experiment 1. The standard deviations are shown in the parentheses.

	Conditions			
Duration	DF	DN	SD	SS
Long	2.06 (.23)	2.11 (.27)	2.13 (.24)	2.22 (.42)
Medium	1.81 (.25)	1.84 (.22)	1.85 (.23)	2.01 (.38)
Short	1.57 (.30)	1.56 (.28)	1.60 (.28)	1.75 (.35)
Mean Overall	1.81 (.20)	1.84 (.19)	1.86 (.19)	1.99 (.36)

Note. Ratings from 1 to 3 were used to categorize the stimulus duration, with 1 = short, 2 = medium, and 3 = long. For conditions, SS = same-object-same-location; SD = same-object-different-location; DN = different-object-near-location; DF = different-object-far-location.

Table 3

Mean perceived duration for the duration categorization task of Experiment 2. The standard deviations are shown in the parentheses.

	Conditions			
Duration	DF	DN	SD	SS
Long	2.22 (.30)	2.23 (.29)	2.24 (.22)	1.92 (.55)
Medium	1.99 (.25)	1.98 (.24)	1.94 (.24)	1.75 (.47)
Short	1.72 (.30)	1.71 (.31)	1.72 (.27)	1.58 (.38)
Mean Overall	1.98 (.23)	1.97 (.22)	1.97 (.20)	1.75 (.44)

Note. The notations for the conditions are: SS, same-object-same-location; SD, same-object-different-location; DN, different-object-near-location; DF, different-object-far-location.

Table 4

Mean reaction times (in ms) and error rates (percent incorrect) for the letter discrimination task of Experiment 3. The standard deviations are presented in the parentheses.

	Conditions		
Duration	DN	SD	SS
	Reaction Times		
Long	550 (186)	537 (169)	526 (155)
Medium	529 (157)	535 (165)	517 (157)
Short	545 (157)	536 (152)	515 (153)
Mean Overall	541 (164)	536 (158)	519 (154)
	Error Rates		
Long	5.9 (5.8)	7.5 (7.7)	6.6 (4.9)
Medium	9.2 (9.7)	8.3 (6.9)	8.0 (6.4)
Short	8.3 (8.1)	7.8 (7.4)	7.5 (6.3)
Mean Overall	7.8 (7.2)	7.9 (6.2)	7.4 (5.5)

Note. The notations for the conditions are: SS, same-object-same-location; SD, same-object-different-location; DN, different-object-near-location.

Table 5

Mean perceived duration for the duration categorization task of Experiment 3. The standard deviations are shown in the parentheses.

	Conditions		
Duration	DN	SD	SS
Long	2.18 (.21)	2.15 (.23)	2.24 (.24)
Medium	1.89 (.20)	1.88 (.24)	1.95 (.17)
Short	1.51 (.27)	1.61 (.33)	1.62 (.32)
Mean Overall	1.86 (.15)	1.88 (.18)	1.94 (.17)

Note. SS refers to the same-object-same-location condition; SD, the same-object-different-location condition; and DN, the different-object-near-location condition.

Table 6

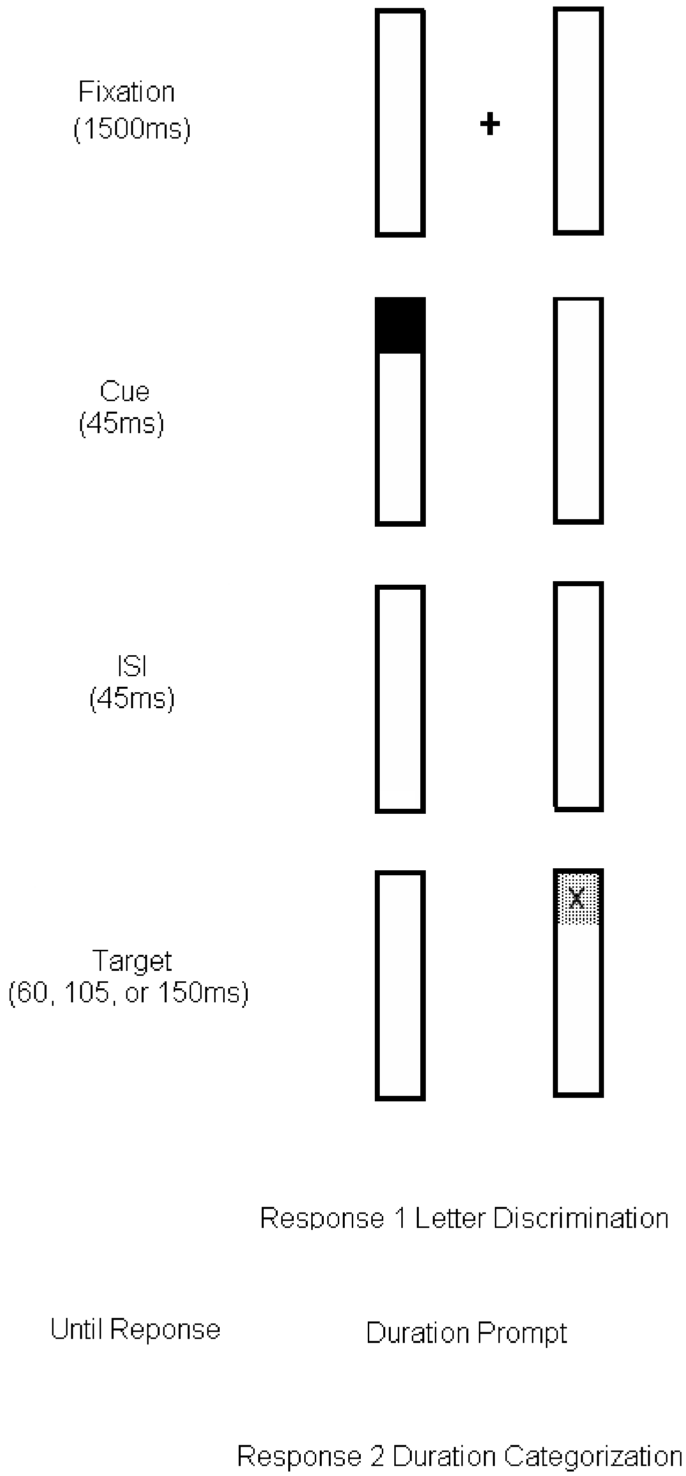
Mean perceived duration for the duration categorization task of Experiment 4. The standard deviations are shown in the parentheses.

	Conditions		
Duration	DN	SD	SS
Long	2.21 (.23)	2.16 (.24)	2.12 (.17)
Medium	2.00 (.17)	1.95 (.18)	1.93 (.19)
Short	1.71 (.33)	1.69 (.29)	1.70 (.31)
Mean Overall	1.97 (.14)	1.93 (.14)	1.92 (.13)

Note. SS refers to the same-object-same-location condition; SD, the same-object-different-location condition; and DN, the different-object-near-location condition.

Figure Caption

Figure 1. An example of stimulus displays from Experiment 1. On each trial, a non-informative cue was presented in one of four locations, followed by the presentation of a target letter whose duration varied from 60 ms to 150 ms. Observers' primary task was to judge whether the target letter was an X or an O. As soon as they responded to the letter discrimination task, they were prompted to categorize the stimulus duration on a 1-3 scale, 1 being the shortest, and 3 the longest.


Fixation
(1500ms)
+
Cue
(45ms)
ISI
(45ms)
Target
(60, 105, or 150ms)
X
Response 1 Letter Discrimination
Until Reponse
Duration Prompt
Response 2 Duration Categorization