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RESEARCH ARTICLE

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Estimating the components of the gap effect

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Abstract The gap effect refers to the finding that saccadic latencies are typically reduced when a fixation point is removed prior to the appearance of a peripheral target. This reduction in saccadic reaction time (SacRT) is thought to be due to a general warning effect and an oculomotor specific fixation offset that occur when the fixation point is removed. In order to estimate the contribution of each of these effects to the overall gap effect, this paper introduces a new manipulation, the partial-gap trial, where the fixation point undergoes a change in size prior to the presentation of the target. The partial-gap trial is presumed to provide the visual warning effect of the fixation offset (i.e. similar to that in a gap trial) but does not provide the fixation offset effect (FOE). When the fixation point was abruptly reduced in size before the presentation of the target, the estimated decrease in SacRT due to the visual warning effect was 5–7% and did not differ in the presence or absence of an auditory warning signal. It was found that auditory warning effect and the FOE interacted in reducing SacRTs. Additionally, when the fixation point was abruptly increased in size before the presentation of the target, SacRTs were slower than when the fixation point did not change in size and remained present for the entire trial (i.e. an overlap trial). We conclude that this new partial-gap paradigm is a useful method for researchers wishing to separately examine FOE and visual warning effects.

Estimating the Components of the Gap Effect

The latency to initiate a saccadic eye movement can be dramatically decreased if the fixation point is removed briefly before the appearance of a peripheral target (Saslow 1967). Following this original study, the reduction in saccadic reaction time (SacRT) has been termed the "gap effect", referring to the temporal gap between the offset of the fixation point and onset of a peripheral target (Reuter-Lorenz et al. 1991; Klein and Kingstone 1993). Over the past two decades, the gap effect has been proven to be extremely robust, having been found with anti-saccades (Biscaldi et al. 1996; Forbes and Klein 1996), eye movements and limb movements (Bekkering et al. 1995; Pratt et al. 1999), peripheral exogenous targets and central endogenous targets (Abrams et al. 1998) and across the lifespan (Pratt et al. 1997; Munoz et al. 1998).

Despite the robustness of the gap effect, the nature of the underlying mechanism has been the source of some controversy. Over the years, a wide variety of theories have been proposed to account for the reduction in saccadic latencies that occur with the removal of the fixation point. These theories have implicated the disengagement of covert attention (Fischer and Weber 1993), the facilitation of sensory processing (Reulen 1984a, 1984b) and a general oculomotor readiness (Saslow 1967). In addition to those possible explanations, Kingstone and Klein (1993a, 1993b; see also Klein and Kingstone 1993; Forbes and Klein 1996) have proposed a two-component theory of the gap effect. In their theory, the removal of a fixation point prior to the onset of a target initiates two independent components, which together produce the gap effect. One component is a response preparation effect that occurs because the fixation offset acts as a general warning signal that the appearance of the target is imminent. The other component is a fixation offset effect (FOE), which is a facilitatory effect specific to the oculomotor system. The FOE appears to be due to the release of inhibition in the superior colliculus (SC) that serves to prevent eye movements during active fixation (Schiller et al. 1987; Munoz and Wurtz 1992). Thus, when the fixation point is removed, there is a general warning signal that the target is forthcoming, and there is disinhibition in the SC that allows the eye movement to

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be initiated more quickly. Together, these two components produce the gap effect.

Recently, Shafiq et al. (1998) were able to estimate the approximate contributions of the warning effect and the FOE on the overall gap effect. In one experiment, auditory fixation points and peripheral targets were used. Thus, in gap trials, the fixation tone would be removed prior to the onset of the auditory target. Because there are no known inputs from auditory cortex that directly connect to the fixation cell units in the SC, their basic assumption was that any advantage in SacRTs from removing the fixation tone would be due to something other than a visual FOE. In another experiment, they used visual fixation points and targets, so that the removal of the fixation point would yield both a warning effect and a visual FOE. When the targets in both domains had the same eccentricity (15°), they found a gap effect of 30.2 ms in the visual domain and gap effects of 17 ms (experiment 1) and 13 ms (experiment 2) in the auditory domain. Shafiq et al., noting that the 17 ms estimate from experiment 1 may be more reliable, suggested that the traditional gap effect is approximately 50% due to a visual FOE.

There are, however, some reasons to believe that the estimate of the FOE provided by Shafiq et al. (1998) may not be accurate. One reason is that the overall SacRTs differed between the two domains (when target eccentricity is held constant at 15°), with mean SacRTs in the auditory domain ranging from 161 ms to 201 ms, while slower SacRTs were found in the visual domain (204–234 ms). Thus, it is not clear whether the estimates should be made on the absolute values of the SacRTs or the relative values of the SacRTs (i.e. equating for differences in overall SacRT). Another reason is that Shafiq et al. chose to compare gap trials with no-gap trials rather than overlap trials (in a no-gap trial, the fixation point offset is simultaneous with the peripheral target onset). Typically no-gap trials yield faster SacRTs than do overlap trials (for an example of this, see experiment 2 of Shafiq et al. 1998), raising the possibility that the no-gap trials themselves have a warning signal effect and possibly even a FOE. The difficulty is that it is not possible to determine which component yields faster SacRTs in the no-gap trials. The reduction in no-gap SacRTs is not trivial, as Shafiq et al. reported a 13-ms advantage for gap trials over no-gap trials and another 13-ms advantage for no-gap trials over overlap trials (experiment 3). Given these potential problems, it is important to compare the Shafiq et al. estimates with those derived from a different experimental design.

The present study sought to estimate the contribution of the warning effect and the FOE entirely in the visual domain. To do so, we used an experimental design that included three types of trials crossed with two sizes of the fixation point. The three trial types were the typical gap and overlap trials and the addition of the new partial-gap trial. Also, two different fixation points were used, one of 5 pixels in diameter and one of 7 pixels in diameter. Turning first to the 5-pixel condition, the 5-pixel fixation point was removed 200 ms before the onset of the target in gap trials or remained present in overlap trials. However, in the partial-gap trials, the fixation point was initially 7 pixels and then abruptly “shrank” to a diameter of 5 pixels 200 ms before the presentation of the target. Thus, the amount of area of the fixation point removed in the partial-gap trials was the same as that removed in the gap trials, while the final size of the fixation point in the partial-gap trials was the same as in the overlap trials. This partial-gap trial should provide the same warning effect as the gap trial (i.e. same amount of fixation point offset) with none of the FOE (i.e. size of fixation the same as in the overlap trial). In other words, an estimate of the warning effect can be made by subtracting the partial-gap SacRT from the overlap SacRT and an estimate of the FOE can be made by subtracting the gap SacRT from the partial-gap SacRT.

Although the gap, partial-gap, and overlap trials in the 5-pixel fixation point condition provide the information needed to estimate the warning and FOE, another fixation point condition is required for the experiment. This is because the partial-gap trial in the 5-pixel condition is unique, since it has a larger initial fixation point than the other two conditions. This would inform subjects about the upcoming trial and may affect their responses. To provide the needed counterbalance trials for the experiment, a 7-pixel fixation point condition was also used. In this condition, the gap and overlap trials used a fixation point 7 pixels in diameter, while the partial-gap trials used a fixation point that began at 5 pixels and then abruptly expanded to 7 pixels. The same timing that was used in the 5-pixel condition was used in the 7-pixel conditions. Because the two fixation conditions and three trial types were randomly ordered in the experiment, subjects could not anticipate what trial type was forthcoming based on the size of the fixation point. In addition, the two fixation-point conditions allow for the comparison between shrinking and expanding partial-gap trials and between the overall gap effect sizes produced by differently sized fixation points.

In addition to estimating the magnitudes of the two components, we also examined the effect that an auditory warning tone has on the gap effect. Several studies (Reuter-Lorenz et al. 1991, 1995; Bekkering et al. 1995) have sounded a short warning tone in both gap and overlap trials (with the tone occurring the same time as the fixation offset did in the gap trials). Ostensibly, this was done to equate the warning signal effect in the two trials. However, it may be that a visual warning effect provides a much greater warning effect than does an auditory tone. In order to examine the usefulness of an auditory warning tone, the experiment was blocked so that the subjects received the warning tone on all trials in either the first or second half of the experiment.

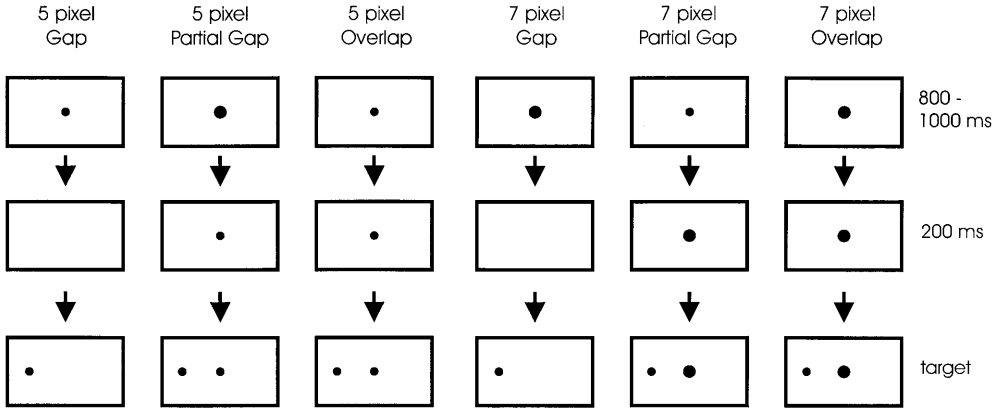

Fig. 1 The trial sequences used in the experiment. The peripheral target was equally likely to appear to the left or right of fixation. See the text for details

Method

Participants

Twelve University of Toronto undergraduate students participated in a single 60-min session. All participants did not wear corrective lenses and received course credit for their participation.

Apparatus

Participants were seated at a table in a dark, sound-attenuated room. To ensure that their heads did not move during the experiment, their heads were placed in a chin/head rest. The distance between the monitor and the chin/headrest was 44 cm. For each participant, the position of the left-eye was monitored with a scleral-reflectance device (Applied Science Laboratories, Model 210) mounted on a spectacle frame.

Data analysis

Samples of eye position were digitised and recorded at 1000 Hz. The eye-movement monitor was calibrated at the beginning of each session, and the calibration was checked at the beginning of each trial. Saccadic eye movements were detected by differentiating and filtering the signal obtained from the eye-movement monitor. A saccade was defined to be the first moment in time at which the velocity of the eye exceeded 10°/s and remained above that value continuously for at least 10 ms, while subsequently exceeding 35°/s. The end of the saccade was defined to be the first subsequent moment in time at which the velocity of the eye fell below 10°/s.

Procedure

The sequence of events on a trial is presented in Fig. 1. Each trial began after the participant was correctly fixating on the fixation dot, which was 3 pixels in diameter. After proper fixation, the fixation point then expanded to either 5 pixels in diameter (approximately 0.28° of visual angle in diameter, resulting in an area of approximately 20 pixels) or 7 pixels in diameter (approximately 0.39° in diameter, resulting in an area of approximately 39 pixels). Following the change in size to the 5-pixel (small) or 7-pixel (large) fixation point, there was a variable foreperiod of either 800, 900 or 1000 ms. In the overlap trials, the target (a dot) subsequently appeared either to the left or right of fixation (with either the 5-pixel or 7-pixel fixation point). In the gap trials, the fixation point (either 5 pixel or 7 pixel) was removed 200 ms before the onset of the target. In the partial-gap condition, there were two possible conditions depending on which size of fixation point appeared at the beginning of the trial. When the 7-pixel fixation point was first presented, the partial gap consisted of abruptly shrinking the fixation point from 7 pixels to 5 pixels in diameter 200 ms before the onset of the target. When the 5-pixel fixation point was first presented, the partial gap consisted of abruptly expanding the fixation point from 5 pixels to 7 pixels in diameter 200 ms before the onset of the target. In all trials, the targets were dots located either 10° to the left or right of the fixation dot, and the participants were instructed to look to the target as quickly and accurately as possible. In half of the trials, an auditory warning tone (500 Hz for 50 ms) was onset 200 ms before the presentation of the target on gap, partial gap and overlap trials.

Design

Each participant performed 112 trials of each of the three trial types (gap, partial-gap and overlap) for a total of 336 trials. In half of the trials for each trial type, the fixation point was small at the time of target presentation (5-pixel gap, 5-pixel overlap, 5-pixel partial gap). The partial gap in this condition had the fixation point change from 7 pixels to 5 pixels. In the other half of the trials, the fixation point was large at the time of target presentation (7-pixel gap, 7-pixel overlap, 7-pixel partial gap). The partial gap in this condition had the fixation point change from 5 pixels to 7 pixels. All of these trials were randomly ordered and the location of the target was equally likely to be left or right of fixation. However, the presentation of the auditory warning tone was blocked and participants were informed that there would, or would not, be a short auditory tone preceding the presentation of the target. The blocking of the auditory tone was counterbalanced so that half the participants received the tone for the first 168 trials, while the other half of the participants received the tone for the second 168 trials. Short rest breaks were given after every 84 trials.

Results and discussion

Trials in which SacRTs were less than 80 ms or greater than 500 ms, or in which the eye movement was not greater than 3° in the direction of the target, were excluded from the analysis. Overall, participants made errors in less than 2% of the trials. The mean SacRTs appear in Fig. 2 and were analysed using a 2 (fixation point: small and large) × 2 (auditory warning signal: tone and no-tone) × 3 (trial type: gap, partial-gap and overlap) analysis of variance (ANOVA). There was a main effect of fixation point [$F_{1,11}$=26.5, mean standard error (MSe)=71, P<0.0005], with faster SacRTs for the 5-pixel fixation point (180 ms) than for the 7-pixel fixation point (187 ms). There was also a main effect for the auditory

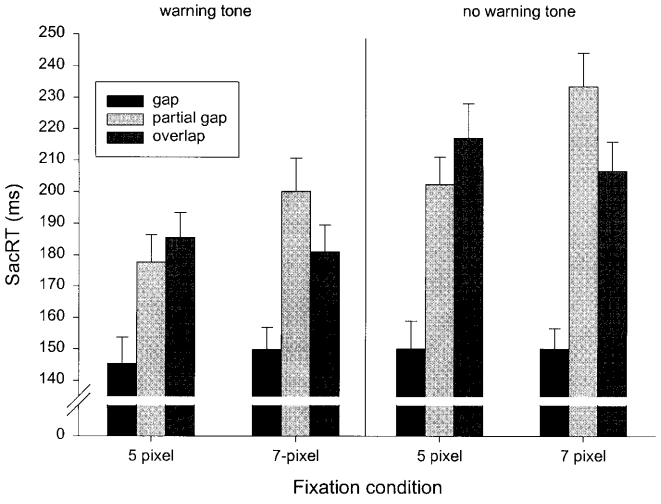

Fig. 2 Mean reaction times (*RTs*) from the correct trials for the gap, partial-gap and overlap trials for both the 5-pixel and 7-pixel fixation points and with the presence or absence of the auditory warning tone

signal ($F_{1,11}$=17.5, MSe=825, P<0.002), with SacRTs of 193 ms without the tone and 173 ms with the tone. Thus, there was evidence of an auditory warning effect. In addition, there was a main effect for trial type ($F_{2,22}$=128, MSe=336, P<0.0001). The fastest RTs occurred in the gap trials (149 ms), followed by the overlap trials (198 ms) and, finally, the partial-gap trials (203 ms).

The auditory warning signal by trial-type interaction was significant ($F_{2,22}$=17.6, MSe=158, P=0.0001), with slower SacRTs in the partial and overlap trials without the auditory warning tone than with the warning tone. The fixation point by trial type interaction was also significant ($F_{2,22}$=34.2, MSe=109, P<0.0001), as partial gap trials yielded SacRTs faster than overlap trials in the 5-pixel condition but slower SacRTs in the 7-pixel condition. The auditory warning signal by fixation point interaction was not significant ($F_{1,11}$<1). Finally, the three-way interaction was not significant ($F_{2,22}$<2.2, P>0.12).

The purpose of the present experiment was to determine the contribution of warning effects, visual and auditory, and the FOE to the gap effect. Because the trials in the 5-pixel condition were designed for this purpose, while the trials in the 7-pixel condition were designed to provide counterbalance to the experiment, the findings from each condition will be discussed separately.

5-Pixel condition

The major finding from the 5-pixel condition is that the warning effect component produced by the visual offset of the fixation point occurs regardless of the presence or absence of a warning tone. When no auditory warning signal was present, the gap effect was 67 ms (overlap SacRT minus gap SacRT) and the estimated warning effect was 15 ms (overlap SacRT minus partial-gap SacRT). When the warning tone was present, the gap effect was smaller at 40 ms (overlap minus gap) as was the estimated warning effect at 8 ms (overlap minus partial-gap). These two visual warning effects are not statistically different in magnitude (t_{11}<1.2, P>0.25). In addition to examining absolute effect sizes, the relative size of the visual warning effect can be estimated by considering the effect as a percentage of the baseline SacRT[1] (e.g. overlap SacRT minus partial SacRT divided by overlap SacRT). This calculation yields relative visual warning effects of approximately 5% in the tone condition and 7% in the no-tone condition. As before, these effects are not statistically different (t_{11}<1). Thus, there is evidence for a visual warning effect due to the removal of the fixation point, even in the presence of an auditory warning effect, and that this warning effect provides a relatively consistent reduction in SacRT. It is worth noting that there may be a floor effect in the gap condition (i.e. SacRTs cannot be shorter), which limits the magnitude of the visual warning effects. Thus, although the visual warning effect may be considered a constant, it could be due to an artefact of the paradigm and the absolute minimum time needed to initiate a saccade.

Having found estimates for the visual warning effects with and without the auditory warning signal, it is possible to estimate the remaining components of the gap effect. As before, we will estimate this components in terms of the percentage effect on the mean overlap SacRTs, which serves as the baseline condition. To calculate the total relative FOE, the calculation of partial-gap SacRT minus gap SacRT divided by partial-gap SacRT will be used. This yields relative FOE effects of 18% in the tone condition and 26% in the no-tone condition. This difference is statistically different (t_{11}=3.2, P<0.01). Estimating the relative auditory warning effect can be obtained by taking the difference between any tone condition and no-tone condition combination, then dividing by the no-tone condition. This yields relative auditory warning effects of 3% (gap trials), 12% (partial-gap trials) and 15% (overlap trials), and the effect for the gap trials is smaller than for the partial-gap and overlap trials (t values$_{11}$=5.5, P<0.001). Thus, unlike the visual warning effect, which remained constant across auditory warning conditions, the FOE and auditory warning effects interact. More specifically, an auditory warning signal reduces the FOE, while the auditory warning effect is reduced in the presence of the FOE. The likely locus of this interaction is the SC, which does receive fast auditory input (Munoz and Corneil 1995) and is also the site of the FOE (Munoz and Wurtz 1992). It should be noted, however, that auditory inputs do not directly connect to the fixation cell units, but rather auditory and visual signals do converge onto cells involved with saccades (Munoz and Corneil 1995).

Given that the components of the gap effect are not mutually exclusive, it is not possible to determine the precise contribution of each component. Nevertheless, some generalisations may be made. For example, it is possible to make some predictions about the situation in

which all three components underlying the gap effect are present (overlap trials without any auditory signal and gap trials with an auditory signal). In this situation, the faster SacRTs in the gap trials should be due to all three components. Using the estimates derived from the present study, the auditory warning signal will reduce SacRT by about 14%, the FOE will reduce SacRT by about 18% (in the presence of a warning tone) and the visual warning effect will reduce SacRT by about 5% (in the presence of a warning tone). This will result in an estimated total reduction of SacRT of approximately 37%. This estimated percentage is slightly greater than the 33% derived from the actual data in the present experiment.

Although no other study has attempted to separate the visual warning effect from the FOE, other studies have estimated the auditory warning effect and a combined visual effect of FOE plus visual warning. In their prosaccade trials, the findings of Reuter-Lorenz et al. (1995) reveal the same basic pattern of interactions between auditory warning effects and visual effects. In terms of the relative decrease in SacRT, the contribution of the auditory warning signal in Reuter-Lorenz et al. decreased from 12% in overlap trials to 5% in gap trials (comparable with the 15% to 3% decrease found in the present study). Likewise, the visual effect in the Reuter-Lorenz et al. study was greater in the absence of the auditory warning signal (24%) than in the presence of the tone (19%; similar to the 31% to 22% decrease found in the present study). Despite the differences in methods between the two studies, the findings from the present study and that of Reuter-Lorenz et al. suggest that the auditory warning effect may decrease SacRTs by some 12–14% and the visual effects (FOE plus visual warning effect) may decrease SacRts by some 19–23% in the presence of an auditory tone. It should be noted that these estimates do not apply to antisaccades. Much smaller gap effects, combined with much longer SacRTs, were found by Reuter-Lorenz et al. in their antisaccade trials. These findings suggest that the processes that are involved in inhibiting a saccade to a peripheral target and then planning and producing a saccade in the opposite direction also interact with the components of the gap effect.

In examining the gap effect in visual and auditory modalities, Shafiq et al. (1998) estimated the visual effect component of the gap effect to be approximately 50% of the overall effect. However, as noted earlier, there may be some problems with this estimate. Specifically, it may not be possible to compare gap effect sizes across the two modalities because of larger differences in overall SacRTs and the use of no-gap trials instead of overlap trials may not have provided the appropriate baseline SacRT condition. Using overlap trials and a single modality, the findings of the present study and from Reuter-Lorenz et al. suggest that the FOE and visual warning effect accounts for some 65% of the gap effect (i.e., at most, the auditory warning signal can contribute 35% to the gap effect). This figure was arrived at by dividing the average reduction in SacRT due to the visual effect (21%) from the average reduction in SacRT due to the visual effect plus the auditory warning effect (21% plus 13%; see the preceding paragraph for the source of these percentages).

7-Pixel condition

The gap and overlap trials in the 7-pixel condition produced the same basic pattern of SacRTs as did the gap and overlap trials in the 5-pixel condition. Overall, gap effects of 31 ms (with auditory warning signal) and 56 ms (without auditory warning signal) were found with the 7-pixel fixation point, slightly smaller gap effects than with the 5-pixel fixation point. These differences in gap effects were mostly due to overlap trials, as the gap trials with the larger fixation point yielded very similar SacRTs to the gap trials with the smaller fixation point. Presumably, the reduced SacRTs with the overlap trials in the 7-pixel condition reflect the level of inhibition within the SC at the time of the target presentation. From single-cell recording studies, it is known that the superficial layers of the SC contain cells that are sensitive to multi-modal sensory signals, including somatosensory, auditory and visual information, which change with the position of the sensory source relative to the retina (Humphrey 1968; Goldberg and Wurtz 1972).

Unexpectedly, the partial-gap trials in the 7-pixel condition did not have the same effect as the partial-gap trials in the 5-pixel condition. In fact, the effect was completely reversed, as the partial-gap trials yielded longer SacRTs in the 7-pixel condition than the overlap trials. This finding is inconsistent with the results of Ross and Ross (1980), who found that changing the fixation point from a “O” to a “#” (or vice versa) reduced SacRTs. Moreover, the present finding indicates that certain changes in the fixation point prior to the presentation of the target may have detrimental effects on the SacRT, even though they provide a valid and obvious warning signal about the onset of the target.

Why might the reduction in the fixation point have shortened SacRTs while the increase in the fixation point lengthened SacRTs? One possible reason has to do with the difference in the phenomenological experience between the partial gap trials in the 5- and 7-pixel conditions. When the reduction of the fixation point occurs in the 5-pixel condition, the general experience is that the fixated object simply shrank to a different size. That is to say, a single object changed form. This may have also been the general experience in the Ross and Ross (1980) study with the changing fixation stimuli. However, in the 7-pixel condition, the abrupt increase of size in the fixation point actually appears as if a larger fixation object abruptly appeared on top of the smaller fixation object. In other words, it appears as if a second object has abruptly appeared at the same location as the previous fixation point. It may have been that, in this condition, the abrupt increase in the fixation point was perceived as the appearance of a new object and, therefore, a possible

target, and thus a response to that object was prepared and then cancelled. Thus, the longer SacRTs to the actual targets in the partial-gap trials may have occurred because the peripheral targets were presented while the subjects were still recovering from preparing a response to the change in the fixation point. Of course, because the change occurred at fixation, the subjects could not have actually made an eye movement to the location they were already fixated on. However, the "go" signal provided by the increase in size of the fixation point may have interfered with the subsequent "go" signal provided by the actual target. It should be noted that Ross and Ross did examine a condition in which a fixation point abruptly appeared 50 ms before a peripheral target and found a slight, but not significant, reduction in SacRT. In light of the Ross and Ross findings, the precise effects of abruptly expanding the fixation point remain to be determined.

Conclusions

Overall, the present findings indicate that the warning effect provided by the removal of a visual fixation point will reduce SacRts by 5–7%. Moreover, while the visual warning effect remains relatively constant across conditions, the FOE and the auditory warning effect interact to reduce SacRTs. Finally, both the size of the fixation point and the type of change the fixation point might undergo have significant impacts on SacRTs. In conclusion, we would like to suggest that the partial-gap paradigm used in the present experiment is a useful method for researchers wishing to separately examine either the FOE or the visual warning effect. One such possibility is that the paradigm may be useful in the long-standing controversy over the existence of express saccades (Fischer and Weber 1993; Kingstone and Klein 1993b) by examining the distributions of large numbers of SacRTs that occur with gap (warning effect plus FOE) and partial-gap trials (only visual warning effect) under various conditions (target certainty/uncertainty, amount of practice, intensity of the stimuli, etc.). Thus, with the partial-gap paradigm, it may be possible to determine whether various experimental manipulations affect only one or both component(s) of the overall gap effect.

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