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Letter to the Editor

Are the original Roelofs effect and the induced Roelofs effect confounded by the same expansion of remembered space?

Roelofs (1935) first described a perceptual phenomenon in which an observer, when viewing a large rectangular frame whose center is positioned to the left or right of the objective midline, will underestimate the degree to which the frame is offset. More recently, Bridgeman, Peery, and Anand (1997) described a related phenomenon (the induced Roelofs effect) in which a target enclosed by a frame will appear to be displaced in a direction opposite the frame offset; for example, a leftward-shifted frame will induce a rightward error in the perception of the target's location. In theory, both the original and induced Roelofs effects could be explained by a frame-induced distortion of the observer's apparent midline (Dassonville & Bala, 2002; Dassonville, Bridgeman, Bala, Thiem, & Sampanes, 2004; Werner, Wapner, & Bruell, 1953).

A recent article by de Grave, Brenner, and Smeets (2002) sought to directly test the idea that both versions of the Roelofs effect had the same underlying cause. In their initial experiment, de Grave et al. replicated the finding of an induced Roelofs effect (Bridgeman et al., 1997) by asking observers to report the location of a target with respect to straight-ahead. In a subsequent key experiment (experiment 2), observers were asked to report the locations of *both* the target and the surrounding frame, with the prediction that if the original and induced Roelofs effects were caused by the same distortion of the apparent midline, the perceptions of both the target and frame should be affected equally. To the contrary, de Grave et al. found that while the frame was mislocalized as expected, the perception of target location was unaffected by the frame in this condition (i.e., no induced Roelofs effect was seen). Based on these findings, de Grave et al. concluded that the original and induced Roelofs effects must have separate and dissociable underlying causes.

However, we believe that the conclusions of de Grave et al. were incorrectly based on two factors that subtly confounded their findings. Most importantly, de Grave et al. provided a training period before each task, in which observers first attempted to report the location of either a target or a frame (with trial types presented in random order), and then were provided accurate feedback of performance so that accuracy could be improved. However, this feedback would have had an additional unintended consequence in the second experiment. Specifically, on those practice trials in which observers were required to localize a frame, the feedback would have served to allow observers to overcome the Roelofs illusion itself. For example, imagine a trial in which a frame was presented 5 cm to the left of midline. The original Roelofs effect would have caused the frame to be perceived as being closer to the midline than it actually was, and the observer's perceptual report would have reflected this. However, the experimenter's feedback would have provided the means for the observer to adjust the perceptual scaling to overcome the effect. Thus, the training period would have inadvertently minimized or eliminated the very effect that de Grave et al. were interested in measuring. Furthermore, training was continued until the observers responded correctly on five consecutive trials, which would not be expected to occur until the original Roelofs effect was completely eliminated.

If it is true that the original and induced Roelofs effects have the same underlying mechanism, a training-related elimination of the Roelofs effect would explain the finding by de Grave et al. that there were no frame-induced mislocalizations of the targets in experiment 2. Paradoxically, though, a significant underestimation of frame offset still occurred, suggesting to the authors the continued presence of the original Roelofs effect. This apparent paradox can be explained, however, if one takes into account the confounding influence of an apparent compression of visual space that has been described in several previous reports on the induced Roelofs effect (Bridgeman, 1991; Bridgeman et al., 1997, 2000; a similar compression of visual space has been demonstrated with other paradigms, e.g., Mateeff & Gourevich, 1983; O'Regan, 1984; Osaka, 1977; Sheth & Shimojo, 2001; van der Heijden, van der Geest, de Leeuw, Krikke, & Muessler, 1999). In the data of de Grave et al., this apparent compression of space is seen as an underestimation of target eccentricity that exists independent of the location of the frame. Thus, the compression is an effect that is (in the conceptual but not spatial sense) orthogonal to the induced Roelofs effect. We suggest here that this apparent compression of

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visual space should equally affect the perception of target and frame position. However, while the errors of target localization caused by compression and the Roelofs effect may be measured independently (i.e., by varying target and frame eccentricity, respectively), their effects on frame perception are necessarily confounded, with the magnitude of both effects dependent on frame eccentricity. If the training procedure allowed the observers to overcome the Roelofs effect, the remaining underestimation of frame offset in experiment 2 of de Grave et al. could be attributed to the apparent compression of visual space. If true, one would expect the underestimates of frame eccentricity in experiment 2 (from de Grave et al., Table 1, Dual task frame estimation, Frame gain) to equal the underestimates of target eccentricity (Table 1, Dual task target estimation, Target gain). Accordingly, no significant differences were seen between these effects, regardless of the temporal order of frame and target presentation.

While a recent study from our laboratory focused on the causes of the induced Roelofs effect (Dassonville & Bala, 2002), previously unpublished data from the study allow us to shed some additional light on the apparent compression of visual space. In one version of the task, observers (after providing informed consent) underwent a training session to learn the locations of five possible targets (0.35° diameter, 100-ms duration, located −4°, −2°, 0°, 2°, or 4° from the observer's objective midline, at eye-level). In subsequent experimental trials, observers reported the location of the target (now presented within a large rectangular frame, 21° × 8.5°, 1° thickness, 1-s duration, centered −5°, 0° or 5° from the midline) by pressing 1 of 5 keys on a keyboard (thumb = −4°, index finger = −2°, etc.). Fig. 1A depicts the pattern of reported locations, replicating the findings of experiment 1 from de Grave et al. (2002) as well as the original report of the induced Roelofs effect described by Bridgeman (1991) and Bridgeman et al. (1997). The induced Roelofs effect can be seen as the vertical displacement of the data in the figure, demonstrating that the leftward-shifted frame caused a rightward error in localization and vice versa ($F(2, 18) = 20.84$, $p < 0.001$). Furthermore, an apparent compression of visual space can be seen, with the perceptions of target location biased toward the midline, regardless of frame position ($F(4, 36) = 53.55$, $p < 0.001$). In contrast, neither of these phenomena affected the accuracy of saccadic eye movements directed to the targets by a second group of observers (Fig. 1B; effect of frame, $F(2, 18) = 3.07$ ns; effect of target position, $F(4, 36) = 0.21$ ns).

Although a cognitive (key press) report of target location appears to reflect a compression of visual space, it should be noted that in order for the observers to determine the appropriate response on any given trial, they were required to compare the location of the target with respect to the remembered locations of the five

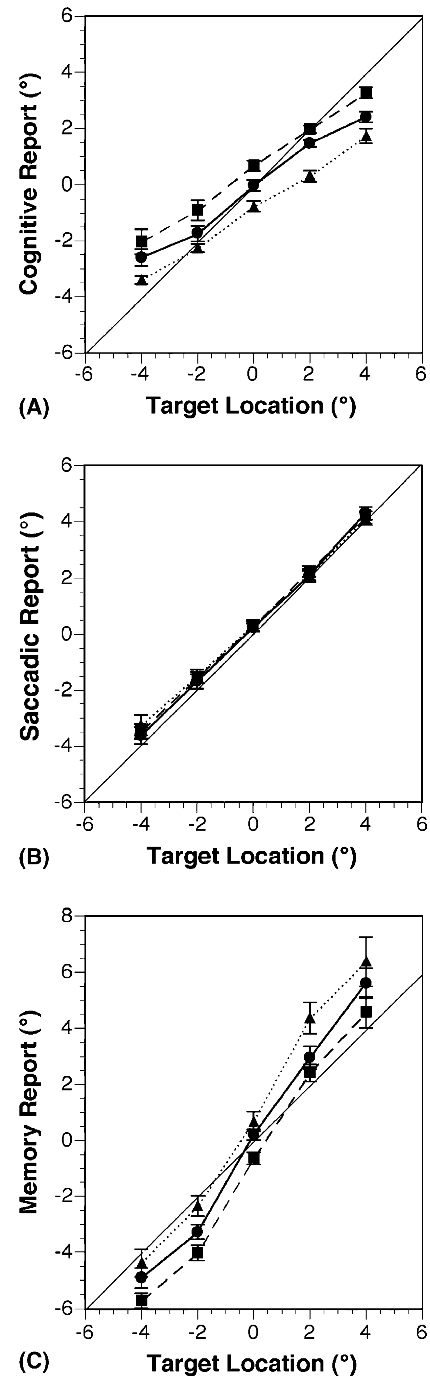

Fig. 1. (A) Cognitive (key press) report of target location, demonstrating an apparent compression of visual space (slope less than one) and an induced Roelofs effect (vertical displacement of the data for different frame locations) for frames offset −5° (■), 0° (●) or +5° (▲) from the midline. (B) Saccadic reports of target location, with no effects of compression or the Roelofs illusion. (C) Saccadic reports of remembered locations of the possible target positions that were learned in an initial training period, demonstrating an inverse Roelofs effect (note different polarity of vertical displacement, compared to data in (A)) and an expansion of remembered space (slope greater than one). These effects can not be attributed to an inaccuracy of the eye tracker used to measure the saccadic responses, since this possible source of error would have equally affected the saccadic responses aimed at target locations in the second experiment (B).

comparison items (possible targets positions) learned earlier. As such, it is possible that the apparent compression noted in the data is actually caused by an *expansion of the remembered positions of the five comparison items*. To test this idea, a third group of observers made saccadic eye movements to the remembered locations of the comparison items, cued by a computer-generated voice that gave the command to move the eye to the remembered location of comparison item "One" = −4°, "Two" = −2°, etc. As can be seen in Fig. 1C, two sources of error affected subject performance. First, an *inverse Roelofs effect for remembered space* can be seen ($F(2, 18) = 17.24$, $p < 0.001$), with the offset frame biasing the remembered locations in the same direction (see Dassonville & Bala, 2002). Second, a nonlinear *expansion of remembered visual space* can be seen ($F(4, 36) = 20.25$, $p < 0.001$), with the memory of the comparison items biased away from the midline, regardless of frame location.

If one assumes that the saccadic reports of the remembered comparison item locations accurately represent the memory of the comparison array that is used to determine the target location in the cognitive (key press) task, then it should be possible to use the data of the sensorimotor task to predict the accuracy of the responses in the cognitive task. A comparison of the predicted errors (Fig. 2A) to the actual errors seen in the cognitive task (Fig. 1A) shows a good fit, accounting for both the induced Roelofs effect and the apparent compression of visual space. This fit is quantified in Fig. 2B. With 95% of the variance accounted for, the data clearly indicate that the induced Roelofs effect and apparent compression of space seen with cognitive judgments can be completely explained by an inverse Roelofs effect and expansion of remembered space that specifically affect the observers' memory of the possible target locations.

Given the similarity in the apparent compression of space seen in our Fig. 1A and in Fig. 3 of de Grave et al., it seems that the compression that they observed could also be attributed to an expansion of remembered space. In their case, however, the expansion would have affected the spatial coordinates of the continuous metric through which observers made their comparisons; for example, a target positioned 3 cm from the midline would have been perceived to occupy the incorrectly memorized location of a target positioned 2 cm from the midline. Given that the perceived frame position was judged using the same metric, it would have been similarly affected.

For this explanation of the data of de Grave et al. to be believable, one has to make the important assumption that the expansion of remembered space is a robust effect, capable of withstanding a training period in which observers are provided accurate feedback about the locations of the practice targets. This seems to be an acceptable assumption, given that an apparent compression of visual space has been seen in every study of

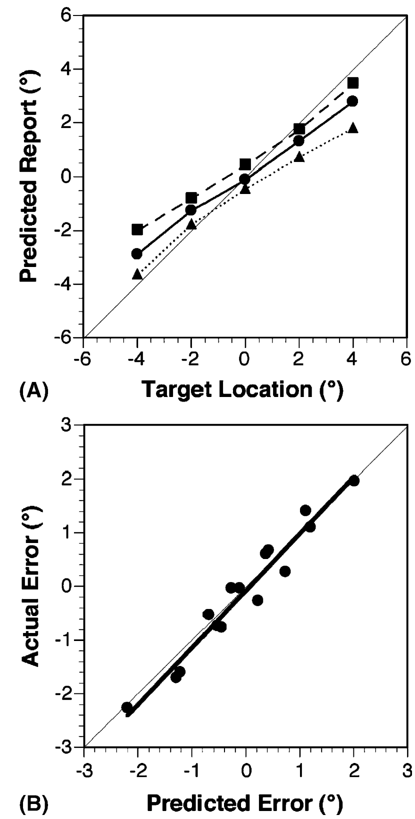

Fig. 2. (A) Predicted cognitive report of target locations, assuming that the saccadic reports of the remembered comparison-item locations (Fig. 1C) accurately reflect the same memory of the comparison array used to make cognitive judgments of target location. The nonlinearity of the expansion of remembered space is not reflected in the predicted compression, since the target locations tested within the cognitive task fall within the central linear portion of the expanded memory of space; that is, the most peripheral targets at −4° and +4° lie approximately at the remembered locations of the comparison items at −2° and +2°, respectively. Symbols reflect frame eccentricities of −5° (■), 0° (●) and +5° (▲). (B) Plot of the regression of the actual errors (Fig. 1A) against the predicted errors (A) for each of the 15 stimulus arrangements (3 frame locations × 5 target locations); $R^2 = 0.95$, $p = 10^{-9}$.

the Roelofs illusion that has required observers to compare target locations with respect to a remembered metric, in spite of the extensive training sessions and feedback that had been provided earlier (Bridgeman, 1991; Bridgeman et al., 1997, 2000; de Grave et al., 2002; see also van der Heijden et al., 1999). On the other hand, the Roelofs effect itself does seem to be susceptible to the effects of training and feedback, as indicated by the data of experiment 2 from de Grave et al.

Taking the confounds of feedback and an expansion of remembered space into account, it now seems that an affirmative answer is appropriate for the question posed in the title of de Grave et al. ("Are the original Roelofs effect and the induced Roelofs effect caused by the same shift in straight ahead?"). In spite of this, we do still agree with the authors' final sentence, in which they conclude that "the absence of the Roelofs illusion in action should not be considered as evidence for a dissociation between visual processing of spatial information for perception and action." Indeed, evidence from our laboratory demonstrates that the absence of a Roelofs effect on sensorimotor responses (Fig. 1B) is fully expected if those responses are guided within the same distorted reference frame as that encoding target location (Dassonville & Bala, 2002).

Comments on de Grave, Brenner, and Smeets's (2004) reply

In their reply, de Grave et al. attempt to answer the question of whether an apparent compression of space can *completely* account for differences in their subjects' abilities to report target and frame locations within their dual task experiment. An important issue, though, is exactly how to interpret the frame gain in the dual task target estimation of the original study (column 6, Table 1 of de Grave et al., 2002). In no trial type (frame first, simultaneous, or target first) were these gains statistically different from 0 and, indeed, de Grave et al. state in the abstract and elsewhere that "the induced Roelofs effect was not present" in this task. If true, a simple test of whether the target gain for target estimation (a measure of the effect of the expansion of remembered space, column 5, Table 1) differed from the frame gain for frame estimation (column 4, Table 1) would determine whether the apparent compression of space could account for the remaining mislocalization of the frame. In no condition did these values significantly differ, which led us to conclude in our original letter that both the original and induced Roelofs effects had been eliminated by training, and were therefore likely caused by the same mechanism.

Contrary to this, de Grave et al., in their reply, suggest that a significant effect of frame in the dual task target estimation *did* exist, if the data of the three trial types are combined to increase statistical power. However, we disagree with this reinterpretation of their data on two separate grounds:

(1) The premise of the authors' reanalysis is that some effect of the frame actually did survive in the dual task. However, even if this were true, there is no reason to believe that the remaining effect should be equivalent across all three trial types. In fact, the single task version of the experiment demonstrates this point directly, with a significant induced Roelofs effect present *only* when the target and frame were presented simultaneously. If one tests only this trial type using the same method of reanalysis as de Grave et al., one would conclude that both effects *were* caused by the same mechanism.
(2) If one does accept that there is a significant effect of frame on target localization in the dual task experiment, it must be noted that the effect is *not* simply a reduced Roelofs effect, since it is opposite in sign (compare the gains in columns 1 and 6, Table 1 of de Grave et al., 2002). Thus, it would appear that the feedback provided to the subjects during training did not simply allow them to reduce or eliminate the gain of the Roelofs effect. Instead, the subjects must have learned an alternative strategy which resulted in an *overcompensation* for the effects of the induced illusion. This being the case, there is no reason to expect this compensation strategy to have equal effects in the frame and target localization tasks (nor in the frame first, simultaneous or target first trial types). It follows that to accurately quantify the Roelofs illusions in the manner of the reanalysis by de Grave et al., additional terms would be required in their Eqs. 1 and 2 to account for the effects of the compensation strategies on the target and frame judgments. Lacking these terms, their reanalysis is confounded by the presence of the compensation strategy, possibly leading to a false impression that it was the magnitude of the Roelofs effects themselves that differed in the two judgments. Unfortunately, it is unclear what form the these additional terms should have, since the mechanism of the compensation is unknown.

Given these objections, we can only conclude that these issues will have to remain unresolved until there is a better understanding of how feedback during training can allow subjects to compensate for the Roelofs effects, original and/or induced.

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