Interactions between Cognitive Space and Motor Activity[1]

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Abstract

Extensive signal processing occurs in sensory systems before perception of object positions. Normally this processing is cognitively opaque, inaccessible to experience or behavioral experiment. Several experimental techniques, however, allow analysis of relationships between unconscious processing and subsequent conscious perception and action. In the induced Induced Roelofs effect, a visual target's perceived position is biased by a large static frame that is offset from the center, an effect that appears in perceptual judgment but not in immediate motor activity. Delayed judgment and delayed pointing both show the effect. All four of these results are due to the frame capturing the straight-ahead, a bias that disappears after stimulus offset. The subject, however, is unaware of the bias, believing the straight-ahead (which affects orientation judgments) to remain accurate. Thus an unconscious bias changes conscious behavior. In a further experiment, inattentional blindness prevents perception of the frame. Nonetheless, the induced Induced Roelofs effect appears. This phenomenon requires two dissociable and sequential unconscious steps, processing the frame and biasing the straight-ahead, before conscious responses are altered.

Orientation in space by vision is a problem that we share with all other mobile animals, and thus we expect mechanisms that achieve this orientation to be effective after a long period of biological evolution. Though the visual properties of the world appear to us instantaneously and effortlessly, a vast amount of neural processing must occur before a person perceives even the simplest aspects of the environment. This processing, critical to a principled understanding of perception and of visually guided action, has been studied in several ways.

Physiologically, we know a lot about receptive fields of single neurons in the visual system, and something about how these neurons are connected. We know which of dozens of cortical areas are active during perceptual discriminations and actions involving various parameters of visual stimulation (Van Essen, Anderson & Felleman, 1992). A functional analysis of sequential stages of processing at the level of behavior, however, is just beginning. In this paper we describe recent experiments pointing to a series of reorganizations of visual material that occur before perception or action take place.

The analysis concerns spatial orientation, measuring both the perceived and the motorically indicated angles of targets relative to the body. While translations are specific to the distances of targets, angles are preserved at any distance, so the results generalize to any distance from the observer. In a natural environment, of course, it is the observer who moves in an environment that has features at every distance.

Another domain in which unconscious functional precursors of conscious action have been investigated is in language, where priming at various levels, including lexical and semantic, is well documented (Merikle, Joordens & Stolz, 1995). The primes in this domain, however, occur at the same level of stimulation as the responses, the level of linguistic material interpreted as such. Our spatially oriented sensory analysis will instead treat coding of one parameter that affects coding of another parameter, sometimes in a different modality. Finally, the second parameter affects perception and action.

One way to dissect visual processes at a functional level is by analyzing illusions. In analogy to destructive testing by engineers, psychophysical destructive testing requires pushing perceptual processes until they begin to break down, giving us perceptions that no longer match a measurable reality. It is in where and how perception breaks down that we learn about its structure.

One-step Unconscious Influence: The Induced Induced Roelofs effect

An illusion that has proved particularly effective in uncovering stages of spatial processing in the visual domain is the Roelofs effect, a static illusion of visual position. In the Roelofs situation a large rectangular frame is presented to an observer off-center in an otherwise empty visual field, so that one edge is directly in front of the observer. In the absence of other visual stimulation, that edge will appear to be offset in the direction opposite the rest of the frame

(Roelofs, 1935). If the right edge of the rectangle is in front of the observer, for example, the whole rectangle will appear further to the right than it really is.

Recently, the Roelofs effect has been modified to facilitate investigations of spatial processing (Bridgeman, 1991). First, the frame need not have one edge centered; illusions occur whenever the frame is presented asymmetrically in the visual field. Second, a small target within an offset rectangular frame is mislocalized in the direction opposite the frame's offset. Thus, the misperception of frame position induces an illusion of target position; this newly described 'induced Roelofs effect' is a static perceptual mislocalization.

Methods

Extensive work with the induced Roelofs effect has differentiated its properties when measured with two kinds of response (Bridgeman, Peery & Anand, 1997; Bridgeman et al., 2000). A cognitive or symbolic response was defined as a verbal forced choice or a button press, to indicate one of several predefined target positions. The spatial relationship between the angle of the target relative to the self on one hand, and the spatial location of the response on the other, is arbitrary. A motor act, in contrast, is defined as a response such as jabbing the target open-loop (without sight of the hand), where there is a 1:1 isomorphic relationship between target angle and motor aim. Subjects either make a decision about the angle of the target (a cognitive response) or jab it with a finger (a motor response). The responses can occur either immediately or after a variable delay. The target and the eccentric inducing frame always appear simultaneously, remain visible for one sec, and disappear simultaneously, to prevent any apparent motion from affecting the results.

Properties of the induced Roelofs effect

Using these two measures, we have obtained the following four results: 1.) A large and consistent induced Roelofs effect is seen for cognitive measures at 0 delay, but 2.) no induced Roelofs effect is seen for sensorimotor measures. 3.) With increase in response delay the effect appears in the sensorimotor measure, while 4.) the cognitive measure does not change. The motor induced Roelofs effect appears gradually after disappearance of the stimulus array. At 1 sec delay it is not significant; it begins to emerge as a small but statistically significant effect at 2 sec (Figure 1), and by 5 sec it is as large as the cognitive effect.

The result has been replicated many times, most recently in a joint effort of two laboratories (Dassonville et al., 2003), one measuring the motor response as a jab with the finger (Bridgeman) and the other measuring it as a gaze angle (Dassonville). Despite the difference in motor response measures, results collected independently in the two laboratories were closely comparable.

Interpreting the induced Roelofs effect

The difficult theoretical issue is why the induced Roelofs effect should be absent in immediate pointing but present in the other conditions with identical stimulus arrays. The original explanation was that a sensorimotor representation of space, unavailable to perception, maintained a veridical map of space even when perception was biased (Bridgeman, 1991). Recent data call this interpretation into question, however: pointing is biased toward visible landmarks even for immediate motor responses (Diedrichsen, Werner, Schmidt & Trommershäuser, 2004), contradicting the landmark-independent result found when pointing to induced Roelofs targets. How can this discrepancy be resolved?

The explanation for these results begins with another measure, an effect of the Roelofs frame on the subject's subjective straight ahead direction. To measure this, the subject simply points or gazes straight ahead either in darkness or in the presence of the visual inducing frame. In darkness, subjects do quite well at this task, pointing quite close to their geometric centerline, and they find it easy, but it turns out that in trials with an inducing frame, the off-center context biases the straight-ahead direction.

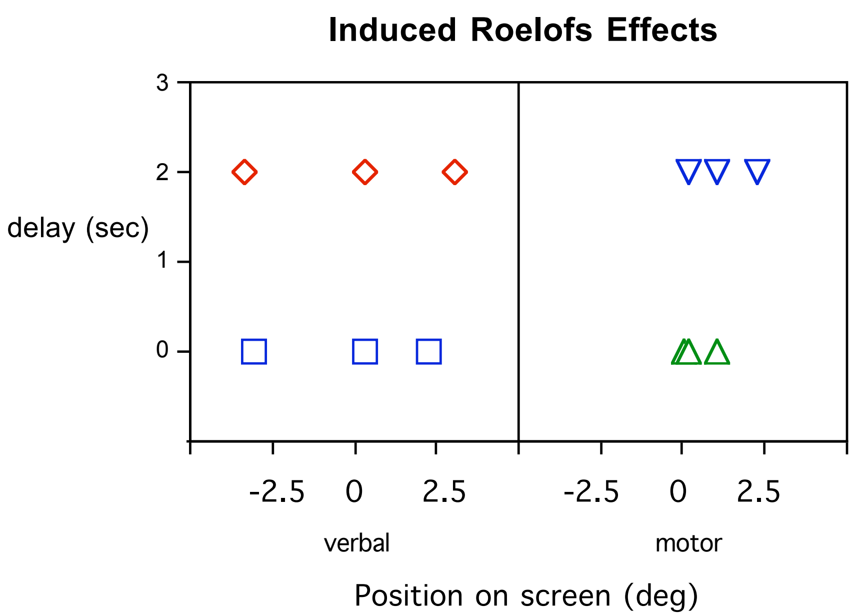

Figure 1. induced Roelofs effects measured with cognitive choice and with motor action, either immediately after stimulus offset or after a 2-sec delay.

The cognitive (verbal) measure is a 5-alternative forced choice for locations 2 deg apart. The motor measure is a jab at the target with the right forefinger, without vision of the hand (open-loop). Each graph shows a small representation of the screen area, with average cognitive or motor indications depicted at the corresponding delay. The three symbols shown for each of the four conditions represent average responses when the frame is in three different positions. Replotted from data of Bridgeman et al. (2000).

Subjects are just as confident in their estimates as before, but they fail to indicate the veridical forward direction. The bias, though, is in the direction opposite the induced Roelofs effect – the straight ahead deviates in the *same* direction as the lateral offset of the inducing frame. Further, the magnitude of the straight-ahead deviation in each subject correlates with the amplitude of that subject's induced Roelofs effect. Correlation coefficients were $r=0.92$ in the Bridgeman data and $r=0.96$ in the Dassonville data (Dassonville et al., 2003).

It is important that the straight ahead is not a visual variable, nor even a sensory event at all. It is an opinion, a judgment of the orientation of the body measured by the orientation of a part of the body (Harris, 1974). Thus it is qualitatively different from the sensory-based judgments and behaviors that it influences. It affects all measures that are calibrated to bodily orientation, in any modality. Indeed, in complete darkness, without any sensory indications of direction at all, subjects show a consistent opinion about their straight ahead, along what Mittelstaedt (1999) defines as an idiotropic vector, generated from within the subject. It can be influenced by external stimuli, but is distinct from them.

For cognitive measures, the straight ahead indirectly affects judgments of position. In a two-stage process, the Roelofs inducing frame pulls the straight ahead in the direction of the frame; then, the subject perceives the visual target's direction relative to the deviated straight ahead. If the inducing frame is on the left, for instance, the subjective straight ahead is pulled to the left, and as a result a target that is objectively straight ahead will be perceived to the right of straight ahead. The subject concludes that the target is to his right because the bias in the straight ahead is unconscious: he still believes that his straight ahead is accurate. The bias of the straight ahead, however, must logically precede the resulting misjudgment of the target position.

This is the sense in which an unconscious effect, the deviation of the subjective straight ahead direction, becomes a precursor to a visual perception, the conscious experience of a target's location in space. Dependence of visual perception on the unconscious, internally stored value of the straight ahead is revealed in the induced Roelofs effect.

It remains to explain why the induced Roelofs effect is always seen in cognitive measures such as verbal report, but is absent in immediate motor responses. Immediate motor action escapes the induced Roelofs effect because subjects calibrate their pointing activity toward a visible target in a biased frame of reference, based on the biased straight ahead. If a Roelofs inducing frame appears on the subject's left, for instance, the straight ahead will be captured by the frame and will also deviate to the left. In pointing, the subject perceives the target to be further to the right than it really is, and initiates a movement toward the right. But the movement is calibrated to the internally registered straight ahead, which is deviated to the left. The two distortions (perception to the right, straight ahead to the left) cancel, resulting in accurate behavior. After a delay, the straight ahead returns to its veridical location, and the subject mispoints.

The delayed cognitive estimate of position retains a induced Roelofs effect because it is based on remembered position of the comparison array. This position does not change with delay after stimulus offset. A subject who perceives a target to be located at position 4 out of a set of 5 previously defined positions, for example, will verbally indicate ‘4’ no matter how long the delay in the response. The memory for the position is a verbal memory, not a spatial value.

Discussion

From an evolutionary or functional point of view, then, we conclude that the motor control system is organized in such a way as to maintain accurate behavior even in the presence of distortions in the straight-ahead direction. This is where geometric accuracy matters in interactions with the outside world; perception is free to wander around, driven by asymmetries in the visual environment, but action must remain on target. We can assume that small induced Roelofs effects are occurring constantly in the natural visual world, where stimulation is seldom completely symmetrical.

The function of perception, in this view, is not to localize targets accurately with respect to the self, but to inform about what is in the world, where objects and surfaces are located relative to one another, and only roughly to localize the self in the visual world. Sensorimotor coordination is more accurate, because it is calibrated with unconsciously registered information.

Two-step Unconscious Influence: Inattentional Blindness

At this point we have established that a visually guided motor response (pointing at a small target) is affected by a precursor coded amodally and unconsciously (the straight ahead). We now go one step further to ask whether the effect of asymmetric visual stimuli on motor behavior will remain when the perception of the Roelofs inducing frame itself is prevented. For the purposes of this paper, perception will be defined as conscious, tested by the possibility of verbal report. If the presence of an object can be noted verbally, then it was perceived, however imperfect the perception might be. If it cannot, then any signal processing that occurs is not perception.

Our strategy is to present a large Roelofs inducing frame, present at high contrast and for a reasonable length of time, but to prevent its perception by diverting attention elsewhere with the phenomenon of inattentional blindness. Mack and Rock (1998) popularized inattentional blindness as a method for investigating the role of conscious awareness in perception. In their experiments, subjects were asked to report the presence of an unexpected stimulus. They often failed to report the appearance of many properties of an unexpected stimulus, even if the eyes were directly fixated on the location of its appearance. We review their methods here because similar methods will be employed in the following experiments.

Mack and Rock (1998) had subjects view a fixation target for 1500 ms, followed by distractor cross for 200 ms, which was then followed by a mask. Subjects judged whether the vertical or horizontal segment of the cross was longer. The two segments differed only slightly in length, making the task difficult. The cross was centered at fixation or parafoveally, within a few degrees of fixation. Typically there were three or four of these non-critical trials before a critical trial. On the critical trial, an unexpected ‘critical stimulus’ was presented along with the cross in one of the four quadrants created by its intersecting horizontal and vertical segments. Immediately following the critical trial, subjects were asked, "Did you see anything on the screen on this trial that had not been there on previous trials?" If they reported seeing something else, they attempted to identify it with a recall or recognition test. In addition to this critical trial, subjects subsequently underwent divided- and full-attention (critical) trials. There was nothing different between these trials and the inattention trial, except for the knowledge that something in addition to the cross might appear in the display. That is, subjects now had a reason to expect that something in addition to the cross might appear.

Method

Our design was similar, except that subjects had two tasks. One was to judge the relative lengths of the arms of a small cross, like the Mack and Rock task; the other was to judge the position of the cross in a 5-alternative forced choice like the choice we had previously offered in Roelofs-effect experiments. Before the experimental trials began, subjects were shown positions numbered 1-5, at -8, -4, 0, 4, or 8 degrees from the participant's midline, and asked to use these positions as choices for the target position. Subjects completed 25 training trials in order to learn the five possible locations of target (distractor cross) appearance. On each trial the target appeared at one of the five positions, in random order. During the experiment we used only positions 2, 3 and 4, anticipating that subjects might mislocalize the targets. Our distractor stimulus, a 21 deg wide x 9 deg high Roelofs inducing frame that surrounded the target, appeared on critical trials 5, 10, and 12. Its center was offset 4 deg to the right of the subject’s center line (Fig. 2). These were categorized as our inattention, divided- attention, and full-attention trials, respectively.

During critical trials, both the cross and frame simultaneously appeared for 100 ms, with the cross at position 2, followed by a mask consisting of a grid of vertical and horizontal lines. The design requires a large number of subjects, because most of the interesting information comes from a single trial, the first appearance of the unexpected frame.

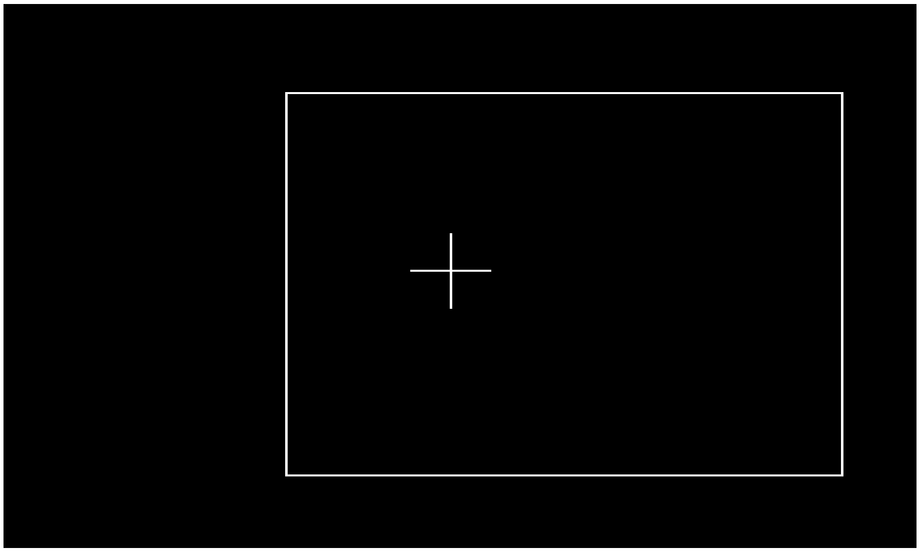

Figure 2. Stimulus array during each critical trial; a large laterally displaced rectangular frame is presented simultaneously with a cross.

This experiment investigates two primary questions: (1) Can a large illusion-inducing stimulus presented unexpectedly go unreported due to inattentional blindness? and (2) If that stimulus goes unreported, will it still impact the perceived location of the target cross?[1]

Results

More than half of 57 subjects (54%) failed to notice the frame on the inattention trial when asked about it immediately after the trial. The answer to the first question was a definite ‘yes’.

To examine the second question, we looked at the localizations of the target in the inattention trials where a frame was presented but not reported. The result was a systematic distortion of the perceived target location in the direction opposite the bias of the frame. The key comparison is the inattention trial with trials 2 and 9, which also had the target at position 2 but had no frame. When the frame was present, the target was estimated to be 3.5 deg to the left of its true location; with the frame absent, the same target position was estimated to be 2.4 deg to the right (Figure 2). Thus the presence of the frame induced a Roelofs effect of 5.9 deg. This analysis suggests that when the target was surrounded by a frame offset to the right, participants tended to perceive the target as being more to the left. In fact, a Scheffe test showed that the difference between Positions 4 and 2 with the frame was not significant ($\underline{p} > .05$). This suggests that participants tended to perceive targets at Position 2 more to the right. The deviation of position estimates toward the center in the no-frame condition is a common characteristic of cognitive measures of position, and has been observed in several studies previously (Bridgeman, 1991; Bridgeman et al., 1997; 2000).

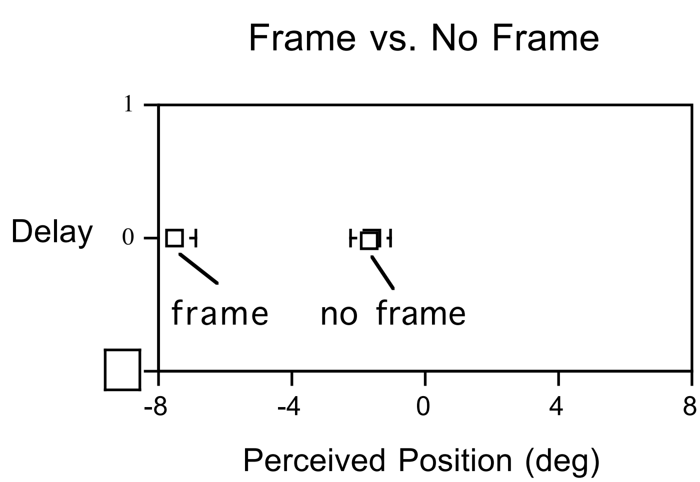

Figure 3. Perceived position of a target located 4 deg to the left of the centerline. Presence of a Roelofs inducing frame offset to the right causes the target to be localized about 5.9 deg to the left of its perceived position without the frame, on average.

A one-way repeated-measures ANOVA was used to evaluate differences in bias due to target location. This factor consisted of Positions 2, 3, 4, and Position 2 with the frame. Results showed significant differences in judgments across this factor [$\underline{F}$ (3, 56) = 17.15, $\underline{p}$ < .01]. A post-hoc Scheffe test showed that mean biases for the inattention, divided-, and full-attention trials were significantly different from the control trials ($\underline{p}$ <.01).

More surprising was a comparison of the subjects who detected the presence of the frame on the inattention trial and those who did not. The two groups of subjects did not significantly differ in their estimates of target position. A between-subjects t-test showed no difference in performance change between the two groups [t (55) = .826, $\underline{p}$ > .05]. These results suggest that the frame did not impact performance on the localization task differently for those who did and did not report the frame.

This analysis suggests that when the target was surrounded by a frame offset to the right, participants tended to perceive the target as being more to the left. Further, this effect did not depend on one being able to report the appearance of the frame, as there was no classification by trial type interaction. So the answer to the second question is also ‘yes’.

Discussion

In order for the systematic mislocalization of the target to occur in the inattention trials, two distinct sequential steps of unconscious processing must occur before the conscious decision is made about which of the positions was presented. First, the unconsciously processed Roelofs inducing frame must bias the subject's subjective straight ahead in the direction of the frame. Second, the resulting unconscious bias must change the subject's perception of the target's position. Logically, the frame's position must be processed in the brain before that position can affect straight ahead, and the straight ahead must be processed before the target can be mislocalized relative to it.

Thus we can identify two sequential, unconscious processing steps that must precede the conscious decision, each coded in a different way. The Roelofs frame is a visual stimulus, processed but not perceived; the subjective straight ahead is not a sensory coding but an opinion about the orientation of the body, influenced by sensory events but separate from them. Its offset is not perceived. It affects the localization of perceptions in any modality, and slowly changes its biased value in the absence of any spatial stimulation at all (a characteristic shown in the first experiment described here, where the induced Roelofs effect reappeared in a motor measure after a delay). This result adds to recent work showing that subjects can sense whether a change has taken place in a visual scene without being able to consciously identify the change (Rensink, 2004).

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Footnote

1. A preliminary abstract of the inattentional blindness studies described here has appeared in the proceedings of the Psychonomic Society 2003 annual meeting.