The Roelofs and Induced Roelofs Effects

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Abstract

The visual image provides important cues for an observer's sense of location and orientation within the world. Occasionally, though, these cues can be misleading, resulting in illusions. In the Roelofs and induced Roelofs effects, for example, a large illuminated frame, offset from the observer's midline in otherwise complete darkness, tends to bias the observer's judgment of straight ahead, causing the position of the frame, and anything contained within it, to be misperceived. Studies of these illusions have provided much insight into the processes that establish an observer's egocentric reference frame, and the manner in which object locations are encoded relative to this frame for perception and action.

Preface

In 2012–13, Ben Lester and I had the pleasure of working with Bruce Bridgeman to write a review of the visual illusions known as the Roelofs and induced Roelofs effects. The review was originally intended as a book chapter, but due to a miscommunication with the editors, it was mistakenly left out of the final publication. While frustrating and disappointing at the time, that miscommunication created the scenario that allows us to share the review in this special issue of *Consciousness and Cognition* dedicated to Bruce's life and works. We are honored once again to serve as coauthors with Bruce, even as we are deeply saddened by the circumstances.

For many years, I have shared with my students the story of how my collaboration with Bruce began, because it is a shining example of Bruce as a scientist, putting data before ego, and as a person, kind and thoughtful. One of my first extended interactions with Bruce occurred at the 2001 meeting of the Cognitive Science Association for Interdisciplinary Learning (CSAIL). In the years before, Bruce had published several papers describing a dissociation in the way perceptual judgments and sensorimotor actions were affected by the induced Roelofs effect, which seemed to provide support for the existence of separate maps of visual space for cognition and action. I was a new assistant professor, and my talk at the conference contained some preliminary data that had led me to a new interpretation of the Roelofs dissociation that directly contradicted Bruce's, so I was a somewhat nervous knowing that he was in the audience. After my talk, Bruce approached me and said something like, "You know, I never thought about it that way," and we agreed to meet later that evening to have a deeper discussion. By the time we met later that day, Bruce had already started developing a paradigm that would provide a direct test of the two interpretations. After we smoothed out the details of an experiment, Bruce proposed that we each do the experiment separately (he in his lab with pointing movements as the motor response, me in my lab with eye movements), with a plan to write up the results in a single manuscript, and the order of authorship determined by whichever interpretation was correct. The results of that collaboration were eventually published in *Vision Research* (Dassonville, Bridgeman, et al., 2004).

My CSAIL presentation could have provoked many reactions in a lesser person — a decision to ignore inconvenient findings, an urge to go back to the lab to find evidence to contradict my interpretation and reinforce his own, a plan to keep for himself the new ideas for follow up experiments that my presentation prompted, etc. Instead, Bruce enthusiastically embraced the challenge and forged a new collaboration to resolve the discrepancies, gladly following the data no matter where it led. In doing so, he provided a striking example of the way science, and scientists, should work, and I'll always be grateful to him for that. Bruce was bright and interesting, fun to talk with, and generous in spirit — he is missed.

– Paul Dassonville

Introduction

In the Roelofs effect (Roelofs, 1936[1]), an observer in otherwise complete darkness is presented an illuminated rectangular frame positioned so that one edge is aligned with the observer's median plane (Fig. 1A). However, the observer typically reports that the frame has a reduced offset; for example, with the frame shifted rightward so that the left edge is straight ahead, the observer reports that the edge appears to lie to the left of straight ahead (Fig. 1B).

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[1] This is often cited as Roelofs, 1935. However, the copy of the paper in our possession, originating from the Bayerische Staats-Bibliothek München, has the bibliographic notation "München Verlag von J. F. Bergmann 1936".

Alternatively, if the observer is asked to position the frame so that one edge lies straight ahead, he or she will typically position the frame with an exaggerated offset in order to compensate for the effects of the illusion.

In a related phenomenon, an offset frame can also induce the mislocalization of an enclosed target (Bridgeman, Peery & Anand, 1997). In this *induced* Roelofs effect, an observer is asked to report the location of the target (for example, by judging its location with respect to the median plane; Fig 2A). However, the presence of the offset frame typically generates a bias in the reported location of the target, with the target perceived to be offset in a direction opposite that of the frame (that is, a right-shifted frame causes the target to be perceived as being offset to the observer's left; Fig 2B).

History

Interest in how an observer determines the locations of objects in the world, 'how the eye knows where the world is', is as old as psychophysics. In the 19th century, Lotze formed the basis for subsequent work on localization with his theory of local signs, which proposed that the location of an image on the retina signals the presence of an object in the corresponding place in the world. It turned out, however, that local signs were not the end of the story; localization of a given object could also be influenced by the positions and motions of other objects in the visual field, as the Gestalt psychologists of the early 20th century pointed out, as well as by the state of the oculomotor system and the posture of the body.

The dynamics of context-dependent localization were thoroughly investigated by Karl Duncker (1929), who showed that motion of a large object (for example, a frame) could induce, in the opposite direction, an apparent motion of an egocentrically stationary smaller object.

Generally the large object appeared more stable or appeared to move more slowly than the small one, even if the reverse was true in the optic array. Today this effect is attributed largely to the involuntary optokinetic reflex tracking the larger object simply because of its extent in degrees of solid angle, without the eye movement being registered in perception (Leibowitz et al., 1983). The oculomotor pursuit effort required to counter the optokinetic innervation is registered as movement of the fixated object.

Duncker had assumed that the relative motion of the spot and frame was responsible for the induced motion. It turned out, though, that true motion was not necessary to induce mislocalization of a target object. Even Duncker demonstrated what he called stroboscopic induced motion, where an instantaneous displacement of a frame induced a smaller perceived displacement of a surrounded target in the opposite direction. He assumed that the transient, rather than the biased location, was responsible for the effect. Between transients the target remained perceptually fixed and mislocalized in a direction opposite that of the inducing frame.

C. Otto Roelofs (1936) went further to describe a mislocalization induced in a static situation. The effect was described in a paragraph of a larger paper on optical localization. The following is a translation of that paragraph in its entirety:

> "Another experiment is the following. A luminous rectangle is visible in an otherwise completely dark room. This rectangle can be moved in the frontal plane. One can now try to bring either the right side or the left side of this rectangle into the apparent optical median plane. In the first case, the left half of the field of sight receives more light stimulation and probably also more motor impulses; in the latter case, the right half of the field of sight receives more light stimulation and probably stronger motor impulses. In fact, the positioning of the right and left side was also unequal. The right side I adjusted

somewhat more to the left, and the left somewhat more to the right (Roelofs, 1936, p. 407, transl. by BB)."

Here Roelofs provides both a description of the mislocalization illusion and a theory of its origin. In his paper it is clear that the motoric impulse is an oculomotor influence: "The motoric impulse is almost always first to be recognized in the eye movement. We must therefore seek phenomena that make the availability of motoric impulses likely, without executing the corresponding eye movement (Roelofs 1936, p. 406)." The theory of motoric impulses faded in the following decades, but is currently being revived in the language of embodied cognition.

Apparently independently, Dietzel (1924) qualitatively described a similar effect, and proposed a mechanism that involved an apparent shift of the median plane. However, quantitative work on the illusion, sometimes called the Dietzel-Roelofs effect, began with Werner, Wapner & Bruell (1953) and later Bruell & Albee (1955a, b).

The existence of this illusion indicates that accurate information about the position of the eyes in the head is not available to perception; otherwise, the observer could simply combine target-on-retina information with retina-in-head information to extract the egocentric position of a target regardless of its history or current visual context. In fact, several studies have shown that the position of the eyes in the head is not accurately perceived (Rock & Halper, 1969; Stark & Bridgeman, 1983). In the absence of such information, other sources of localization must be sought.

One such source is an egocentric localization relative to the observer's midline. The midline, however, is not a perception but an opinion. While proprioceptive and vestibular cues undoubtedly play a role in the formation of this opinion, it can be biased by the visual configuration, in a way that will affect any perception in any modality that relies on localization relative to the midline. Harris (1974) demonstrated this dramatically with a deceptively simple experiment: a cardboard box was inverted and placed over the head of an observer with its sides parallel to the median plane. The straight-ahead direction was measured by having the observer place an unseen finger in the midline, on the outside front surface of the box. This direction was quite accurate. When the box was rotated slightly about a vertical axis, however, the apparent straight-ahead was biased in the direction of the rotation. Thus, visual context biased the observer's opinion about the location of the median plane.

The biased-midline hypothesis has been proposed as a mechanism which accounts for the previously-described cognitive illusion of the Roelofs effect (Werner, Wapner & Bruell, 1953; Bruell & Albee, 1955a, b). The asymmetrical visual stimulus captures the subjective straight-ahead, so that, for instance, a rightward deviated rectangle biases the apparent straight-ahead to the right, and consequently an object in the median plane is perceived as lying to the left of center (Fig. 2C).

A subsequent study compared the two possible sources of mislocalization, object-relative and subject-relative, by changing instructions to subjects while keeping exposure conditions constant (Brosgole, 1968). Using a small spot as the target inside a surrounding frame, Brosgole induced motion in the target by moving the frame. The motion always induced an accompanying shift of the apparent median plane. Brosgole then asked his subjects to indicate the position of a static target when the frame was presented in a fixed off-center position. The apparent deviation of the target was as great as the deviations in the dynamic condition, showing that the effects that had been interpreted as motion contrast could be explained by asymmetrical stimulation without recourse to information from relative motion.

The static condition of Brosgole is equivalent to the effect originally described by Roelofs, with the addition that the offset frame induces an additional mislocalization of the target. This version of the illusion should properly be called an induced Roelofs effect (Bridgeman, Gemmer, Forsman & Huemer, 2000) because mislocalization of the frame induces an opposite mislocalization of the target. Although we feel that the mechanism that drives the induced version of the illusion is the same as for the version described by Roelofs (Dassonville & Bala, 2004a), others have disagreed (de Grave, Brenner & Smeets, 2002).

Dissociation of perception and action

A modern resurgence of interest in the Roelofs effect occurred when Bridgeman et al. (1997) reported that, in spite of the perceptual mislocalizations caused by the induced Roelofs effect, actions guided to the target were accurate under certain conditions. This was demonstrated by asking participants to make open-loop pointing movements toward the target. The accuracy of the pointing movements suggested the existence of separate cognitive and sensorimotor maps of the visual world, the former prone to the illusion and involved in making cognitive judgments, and the latter immune (or at least less prone) to the illusion and involved in guiding motor responses. This dissociation of the effects of the illusion on perception and action seemed to provide supporting evidence for the hypothesis of two parallel paths of visual processing for perception and action (the *Two-Visual-Systems model*; Milner & Goodale, 1995). Bridgeman et al. further demonstrated that the accuracy of the action system was relatively short-lived: If a delay of 4 or 8 s was imposed between the presentation of the target and the onset of the movement, the endpoint of the delayed movement would more likely reflect the effects of the illusion. This delayed effect suggested that the action system lacked its own memory of target position, with the guidance of delayed movements dependent on the memory of the illusion-prone cognitive map.

An alternative explanation for the dissociation of the illusion's effects on perception and action was provided by Dassonville & Bala (2004b). After first replicating the results of Bridgeman et al. (1997), using open-loop saccadic eye movements to the target location as a measure of motor accuracy, Dassonville & Bala demonstrated that the perceptual phenomenon of the illusion was brought about by a frame-induced bias of the observer's apparent median plane (as had been suggested earlier by Werner, Wapner & Bruell, 1953; Bruell & Albee, 1955a, b; Fig. 2C). This was accomplished by asking observers to look (Dassonville & Bala, 2004b) or point straight ahead (Dassonville et al., 2004) immediately after the presentation of a Roelofs-inducing frame. These oculomotor and manual reports were biased in the direction of the inducing frame (Fig. 3A), with a magnitude that was approximately equal to that of the perceptual illusion obtained when asking observers to report the location of a target enclosed within the frame.

This biased-midline hypothesis can also account for the apparent immunity of the motor systems to the illusion-inducing properties of the frame, if one assumes that the movements are guided within the same distorted reference frame that is used to encode target location. For example, a right-shifted frame will cause a small rightward shift in the subjective midline – for the sake of this example, assume that the inducing frame causes the apparent midline to shift 1° rightward from veridical. Thus, a target located directly in front of the observer will be perceived as lying 1° to the left of the biased apparent midline. Subsequently, if the observer guides a pointing movement to the perceived location of the target within that same distorted reference frame (that is, 1° to the left of the biased apparent midline), the action will accurately indicate the target location since the error of motor guidance will cancel the error of target encoding (Fig. 3B; Dassonville & Bala, 2004b). Data further indicating that arm and eye movements are guided within a reference frame distorted by the Roelofs effect was also evident in a paradigm in which observers pointed to (or looked at) the mirror image of a target, reflected across the observer's apparent midline (Dassonville et al., 2004).

Dassonville & Bala (2004b) also demonstrated that the distortion of the apparent median plane was transitory, disappearing a few seconds after the Roelofs-inducing frame is extinguished; presumably, the removal of the frame eliminates the visual cues that were causing the bias, allowing proprioceptive and vestibular cues for straight-ahead to become dominant once again. Ironically, though, it is the elimination of the distortion of the reference frame that provides an explanation for the finding that *delayed* motor responses *do* reflect the illusion. Continuing the example from above, with a target misperceived as lying 1° to the left of the biased apparent midline due to the presence of a right-shifted frame, a delay in the motor response allows for the apparent midline to shift back toward the true, objective midline, dragging the memory of the target location with it (Fig. 3C). A delayed movement would then be guided to a location 1° to the left of the now-veridical subjective midline (that is, the error of encoding the target within a distorted reference frame is no longer canceled by an error of guiding the movement within the same distorted reference frame), resulting in a movement that reflects the illusion.

A similar proposal of a cancelation of errors was later used to explain dissociations of perception and action in response to an illusion caused by a distortion of visually perceived eye level (Li & Matin, 2005), and one caused by a distortion of perceived vertical (Li, Matin, Bertz & Matin, 2008; Dassonville & Reed, 2015). In general, this *Two-Wrongs model* (borrowing a phrase from Li & Matin, 2005) argues that, contrary to Milner and Goodale's (1995) Two-Visual-Systems model, not all dissociations of perception and action require the presupposition of separate visual processing streams as an explanation. Instead, dissociations of perception and action are fully expected to occur with any illusion driven by distortions of the observer's egocentric reference frame: targets are encoded within a distorted reference frame, but this error of target encoding is canceled by the error of motor guidance within the same distorted reference frame.

Level of processing

Recent work with the Roelofs effect has focused on trying to understand the mechanisms that cause the distortion of the subjective midline, by investigating the level of processing at which the offset frame has its effect. Bridgeman & Lathrop (2007) adopted a version of the classic inattentional blindness paradigm (Mack & Rock, 1998) for use with the Roelofs effect, demonstrating that observers were still biased in their perceptual reports of target location even when the inducing frame was not consciously perceived. In spite of this, Lester & Dassonville (2011) demonstrated that a top-down attentional set can be used to modulate the magnitude of the illusion, with attended frames causing a larger effect than unattended frames. However, the Roelofs effect seems immune to another type of top-down processing: observers trained to recognize line segments as being fragments of intact rectangular frames viewed earlier nonetheless showed an induced Roelofs effect appropriate for the individual line segments rather than for the intact frame that they represented (Walter & Dassonville, 2006). Together, these results indicate that the Roelofs effect is modulated through a complicated interplay between spatial information contained in the retinal image and top-down attentional control.

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Figure Legends

Figure 1. The Roelofs effect. **(A)** An illuminated frame is positioned so that one edge is aligned with the observer's median plane. **(B)** The typical observer underestimates the frame's offset, such that the perceived location of the edge is not straight ahead.

Figure 2. The induced Roelofs effect. **(A)** The offset frame contains a smaller target. **(B)** The typical observer reports that the target's location is biased in a direction opposite the frame's offset (for example, a target located directly in front of the observer will appear to lie to the left in the context of a right-shifted frame). **(C)** Underlying basis of the effect. The offset frame causes a bias in the observer's apparent midline (dashed line), resulting in a perceived offset of the target (and the frame) in the opposite direction.

Figure 3. **(A)** When asked to point straight ahead immediately after the offset frame is extinguished, the observer's manual response is biased in the direction of the frame, indicating a frame-induced distortion of the apparent midline (dashed line). **(B)** With a target encoded as lying 1° left of the biased apparent midline, and the resulting movement guided to the location 1° left of the biased apparent midline, the errors of target encoding and motor guidance will cancel, resulting in an accurate movement. **(C)** With a delay imposed between the time that the frame is extinguished and an eventual motor response, the biased apparent midline will drift back toward the objective midline, dragging the memory of the target location (gray circle) and frame (gray rectangle) with it. A motor

response guided within this now-veridical reference frame will reflect the original error of target encoding.

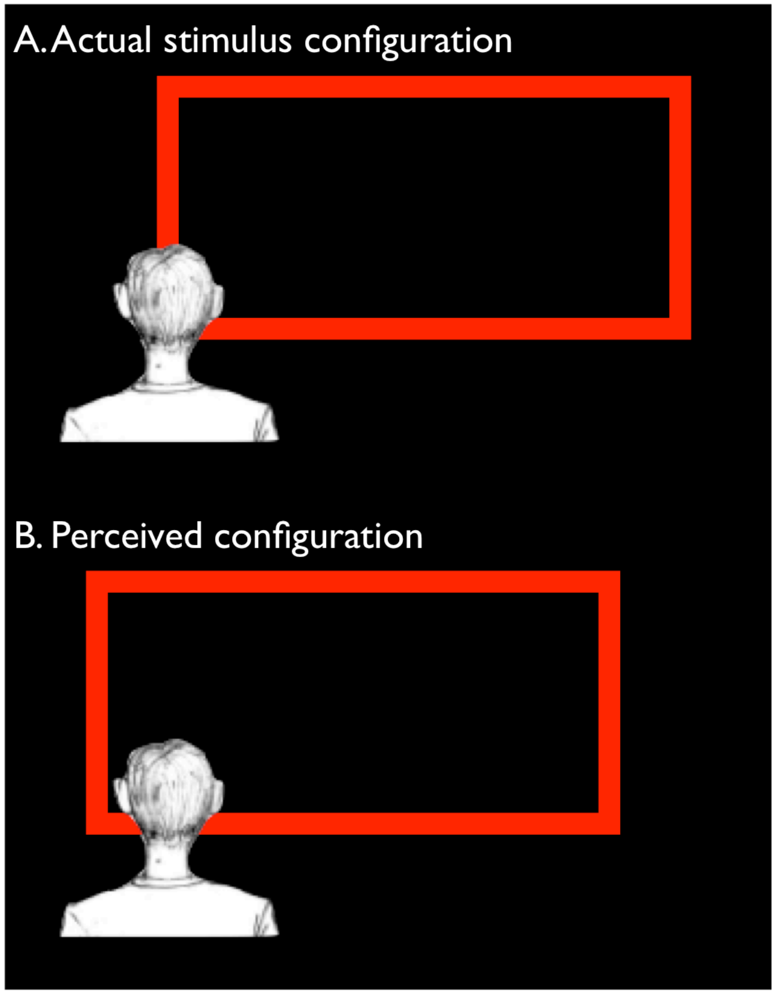
A. Actual stimulus configuration
B. Perceived configuration

Figure 1

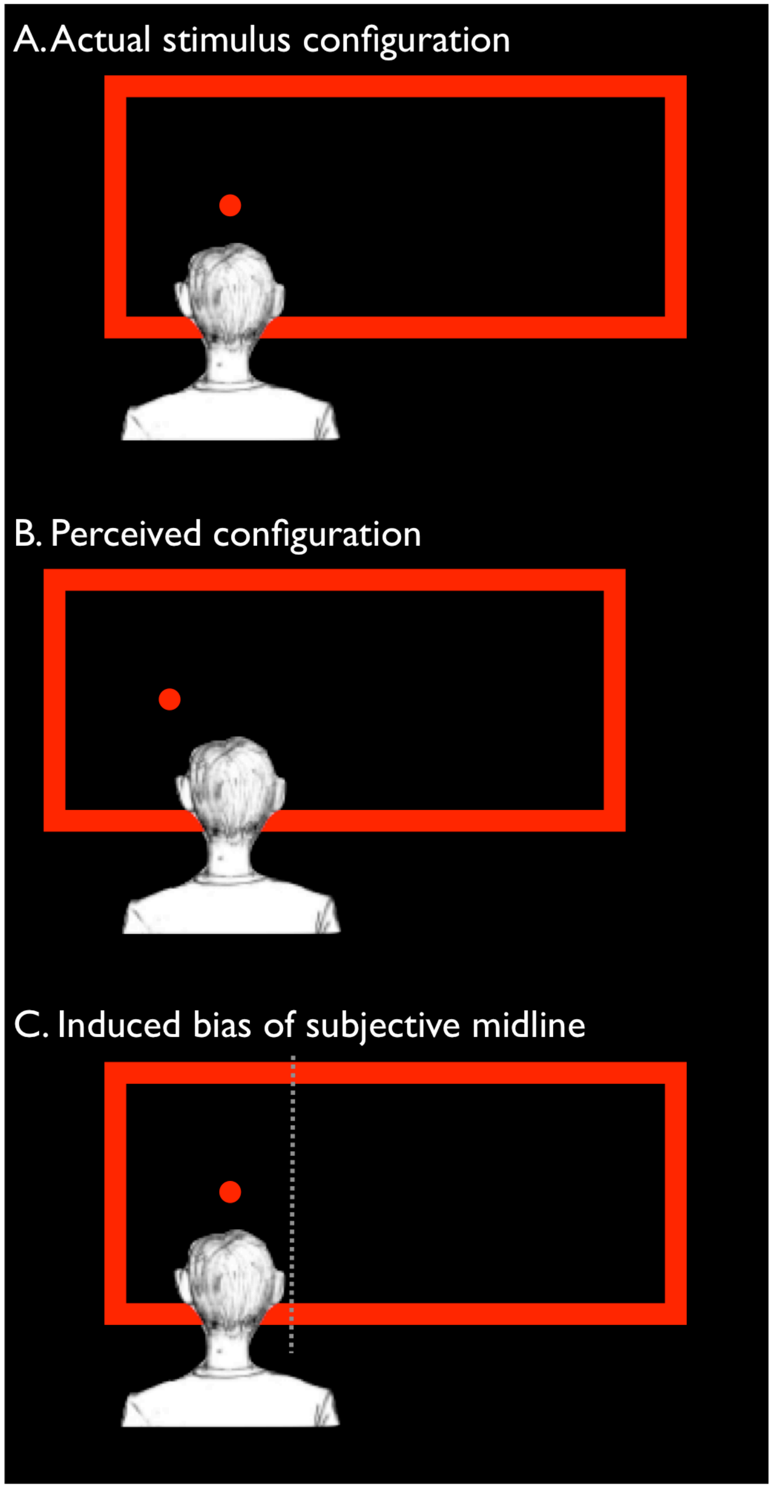
A. Actual stimulus configuration
B. Perceived configuration
C. Induced bias of subjective midline

Figure 2

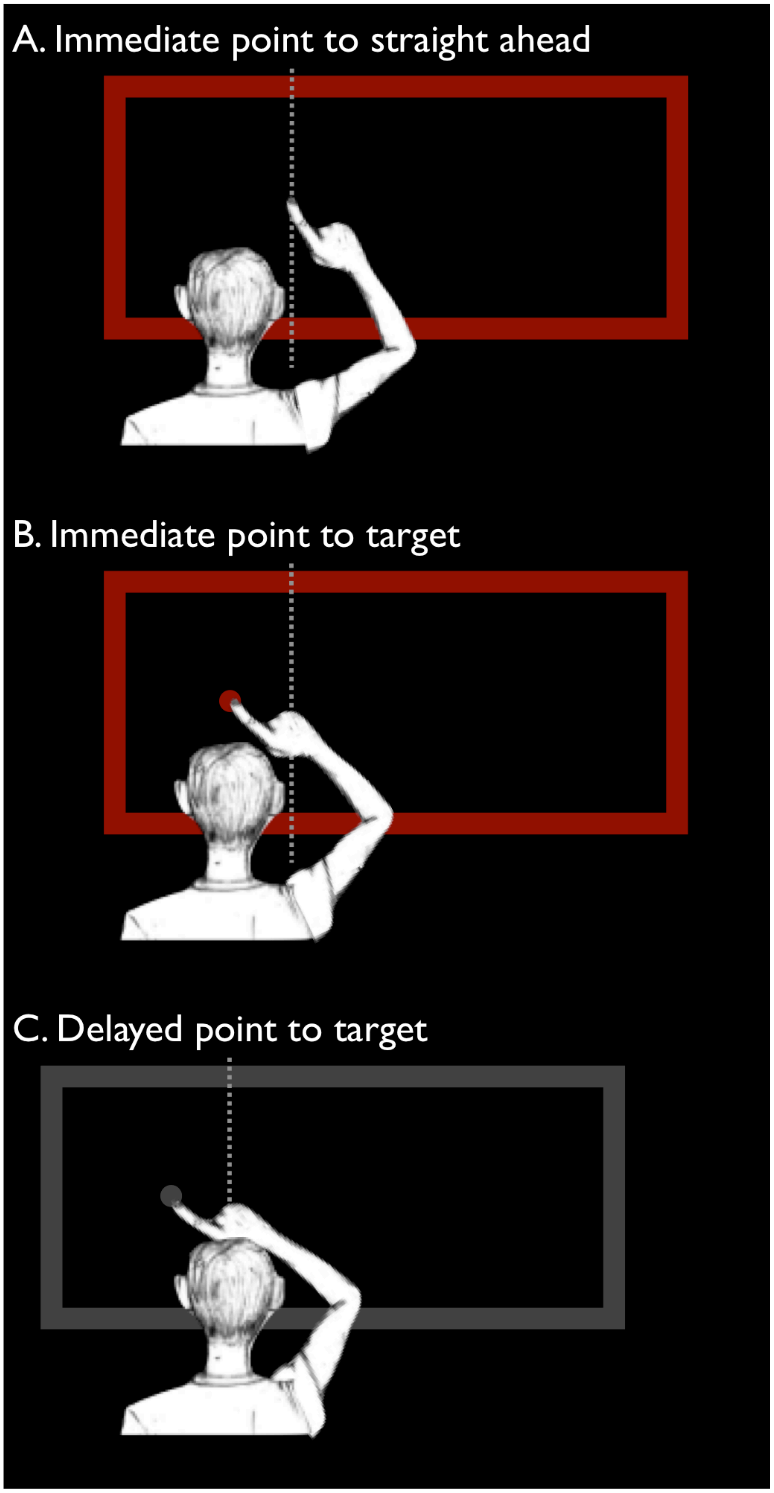
A. Immediate point to straight ahead
B. Immediate point to target
C. Delayed point to target

Figure 3