Representational Momentum Beyond Internalized Physics

Embodied Mechanisms of Anticipation Cause Errors in Visual Short-Term Memory

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ABSTRACT—*Prediction of future motion is necessary in order to successfully deal with moving objects. Implicit measures have been used to evaluate the sources of information used in this task. For instance, observers may be asked to localize the final position of a moving target. Judgments have been found to be displaced in the direction of motion (forward displacement), suggesting that observers have internalized a mental analogue of physical momentum. However, more recent studies have shown that forward displacement may not be caused by cognitive mechanisms alone. Rather, predictive mechanisms at the perceptual and motor levels may contribute to the forward error. Supporting the notion that mechanisms of anticipation may be embodied, the forward error was found to depend on the execution of eye and pointing movements. Also, forward displacement depended on the motion type that was presented (smooth vs. jerky or implied), which suggests that attention moves to the next expected target position to facilitate responses to this position.*

KEYWORDS—*representational momentum; visual short-term memory; naive physics; mislocalization; sensorimotor integration*

In everyday life, people successfully deal with moving objects—for instance when catching a ball or crossing a busy road. Despite how effortless it seems, visually tracking such objects is actually a complex task because their future trajectories must be predicted. For instance, one must place one's hands in the right position before a ball arrives in order to catch it. What rules do people use to make these predictions? One way to answer this question is to ask participants directly about the future trajectory of objects. In their verbal reports, striking discrepancies between Newtonian laws and participants' physical conceptions ("naive physics") have been observed. For instance, some people believe that a ball will exit a spiral tube on a curved path (overview in Kozhevnikov & Hegarty, 2001).

Another way to probe the mental representation of physical rules is to examine error patterns in a task seemingly unrelated to explicit knowledge about such rules: localizing the endpoint of a moving object. This implicit measure has revealed that observers tend to displace the final position of a moving object farther along the direction of motion. One interpretation of this error is that the physical momentum of objects is represented in people's cognitive system (representational momentum); observers may be unable to stop the represented motion instantaneously and a memory error in the direction of motion results. Further studies have shown that other physical principles, such as friction or gravity, may also be implicitly represented in the cognitive system (representational friction, etc.).

In this article, I will show that the perceptual and motor systems also contribute to the prediction of object motion. Some of the mechanisms that were thought to reside in the cognitive system may actually be embodied in the functionality of eye and manual pointing movements. Such a design may make human performance faster and more efficient, because the problem of anticipation is handled where it most urgent: at the level of people's actions.

EMPIRICAL SUPPORT FROM TWO DIFFERENT PARADIGMS

Forward displacement was initially observed by Freyd (Freyd & Finke, 1984), using a series of images implying the rotation of a rectangle. A static rectangle was shown on a computer monitor

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in three different orientations, each for 250 ms, with blank intervals of 250 ms between successive presentations (see Fig. 1). The perceptual impression was that of a rectangle "jumping" from one orientation to the next. The observers' task was to indicate whether a probe rectangle appearing some time after the disappearance of the third rectangle was in the same orientation as the third rectangle or not. Observers were more prone to accept probe rectangles rotated further in the direction of motion as "same" than probe rectangles rotated opposite the direction of motion. This forward error increased when the interval between successive presentations was reduced such that the velocity of the rotation appeared to increase (Freyd & Finke, 1985), supporting the notion of representational momentum.

In another experiment, Hubbard presented participants with a smoothly moving target on a straight path that disappeared at unpredictable positions on the computer screen (Hubbard & Bharucha, 1988). The perceptual impression was that of real object motion. An important methodological detail is that viewing was unconstrained—that is, no fixation mark was presented during target presentation and observers were free to follow the target with their eyes. The observers' task was to point to the final position by moving a mouse cursor. The results converged with Freyd's findings: Observers' memory for the final position of the target was displaced in the direction of motion. However, recent research indicates that the forward displacement observed in Freyd's and Hubbard's experiments may result from very different mechanisms that are unrelated to a cognitive representation of physical principles.

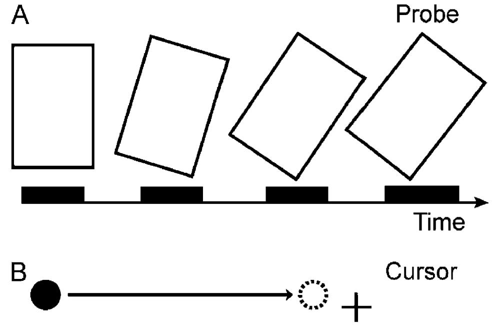

Fig. 1. Illustration of the tests used by Freyd (Freyd & Finke, 1984) and by Hubbard (Hubbard & Bharucha, 1988). To imply motion of a rectangle, Freyd (A) showed a rectangle in different orientations separated by blank intervals (unlike in the figure, the rectangle was shown in the same place on the screen); here, the x-axis indicates the time dimension and black bars mark the intervals during which the target was visible. After the final target rectangle disappeared, a probe rectangle was presented and observers judged whether the probe was in the same orientation as the last target. Hubbard (B) presented continuous horizontal motion of a target. After the target disappeared, observers indicated the final target position (dashed circle) by adjusting a mouse cursor (+ sign).

EFFECTS OF MOTION TYPE: SMOOTH VERSUS IMPLIED MOTION

Implied motion is characterized by the infrequent presentation of a target that makes large steps from one position to the next. The situation resembles motion in a forest: The target object moves and is intermittently covered by trees. In contrast, smooth motion on a computer monitor is generated by target presentations at a high frequency—so high that the human visual system cannot resolve individual presentations but perceives the target as being permanently visible. In this case, the spatial steps between successive presentations are very small. In one experiment, I (Kerzel, 2003b) compared localization of the final position of a smoothly or abruptly moving target on a circular trajectory (see Fig. 2). During target presentation, an eye tracker assured that observers were looking at the fixation mark and did not follow the target with their eyes. Reliable forward displacement was observed with implied motion, but not with smooth motion. Forward displacement decreased as the frequency of target presentation was increased (that is, became smoother). Because the velocity of the different motion types was the same in both conditions, it is difficult to explain the forward displacement in terms of representational momentum.

To account for effects of motion type, one may assume that observers mentally extrapolate the trajectory of a moving object by moving their attention to the next expected target location. When the target vanishes, mental extrapolation overshoots the final target position and the distance between the true final target position and the focus of attention determines the size of the memory bias: With smooth motion, the next step is small, such that the overshoot and the resulting forward shift are also small. In contrast, with implied motion the next step is large, such that the overshoot and the resulting memory error are large. One possibility to test such an account is to measure where in relation to the target observers focus their attention: It was observed that reaction times to stimuli presented ahead of the final target position were shorter, indicating that attention moved further in the direction of motion rather than lagging behind it (Kerzel, 2003a).

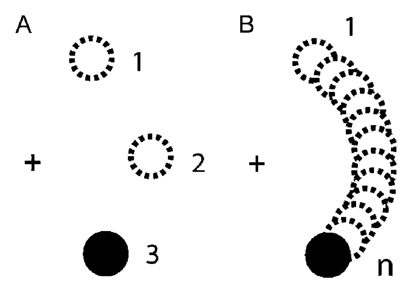

Fig. 2. Schematic diagrams of implied motion (A) and smooth motion (B; Kerzel, 2003b). Observers were instructed to look at the fixation mark (+). In the implied motion condition, successive target presentations (1–3, i.e. clockwise motion) were separated by large blank intervals (as in Fig. 1A), resulting in a weak impression of motion. In the smooth motion condition, the velocity of the target was the same, but a greater number of successive target presentations were presented, at much smaller intervals. The number of steps (n) used to cover a fixed distance during a fixed time interval determines the smoothness of the motion.

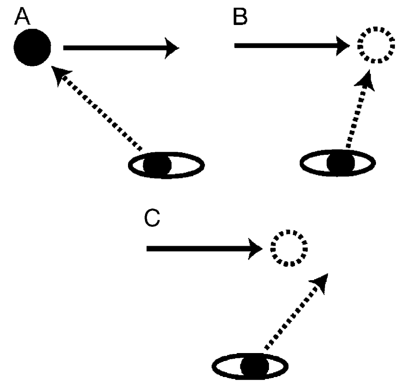

Fig. 3. Oculomotor overshoot after smooth pursuit. When a smoothly moving target is presented, observers typically maintain gaze direction on the target (A) by smoothly moving the eyes at the same velocity as the target, to keep the object stabilized in the region of highest visual acuity. When the motion abruptly stops because the target disappears (B), the motion of the eyes continues for some time such that gaze direction is displaced beyond the final target position (C). Because observers fail to notice that their eye movements continue after the target disappears, they believe that they are still looking at the final target position and mislocalize the final position toward their current gaze direction.

EFFECTS OF EYE MOVEMENT: SMOOTH-PURSUIT EYE MOVEMENTS VERSUS FIXATION

One may wonder why Hubbard and Bharucha (1988) found forward displacement of the final position of a smoothly moving target and I (Kerzel, 2003b) did not. To resolve this discrepancy, one has to consider the natural response of an observer to a smoothly moving stimulus. If the target velocity is slow (less than 50 degrees per second), observers typically pursue the target with their eyes to keep it in the region of the eye that has the highest acuity. These relatively slow eye movements, referred to as smooth pursuit, are in contrast to the rapid movements of the eye called saccades. Smooth-pursuit eye movements depend on the presence of a continuously moving object and therefore cannot be carried out in response to implied motion. One characteristic of smooth pursuit (or any other body movement) is that it cannot be stopped instantaneously. It takes a certain time to send a “stop” command to the relevant muscles. During this time, the body movement continues.

When the observer is following a target with smooth eye movements and the target disappears unpredictably, as in the study of Hubbard and Bharucha, smooth pursuit will continue such that gaze direction is displaced in the direction of motion (see Fig. 3). Because the observer may not be aware of the displacement, she may think that she is still looking at the target, even though she is looking at a position that is displaced in the direction of motion. When asked to localize the target, the observer will then use the current gaze direction as an index to the final target position. This results in a forward error. Consistent with this interpretation, displacement in the direction of motion increases during the first roughly 250 ms, which is approximately the time the eye needs to come to a halt (Kerzel, 2000). In contrast, there is no such time course and no displacement when eye fixation is maintained (Kerzel, Jordan, & Müsseler, 2001). These findings are inconsistent with the idea of representational momentum, because the momentum of the target stays the same irrespective of observer action (fixation vs. pursuit).

Eye movements may also explain other findings that have been attributed to mental analogues of physical laws. For instance, Hubbard showed that forward displacement decreases when the target slides along a two-dimensional surface on the computer screen compared to a condition in which the target (moving at the same speed) is presented in isolation (Hubbard, 1995); the stimuli bear resemblance to a ball rolling across a table and a ball being thrown through the air, respectively. In real life, the former situation would be characterized by much more friction (i.e., between tabletop and ball) than the latter situation (i.e., between air and ball). Because friction reduces the forward momentum of objects in the real world, the reduction of forward displacement in the first (surface) condition supports the hypothesis that friction is represented mentally.

Because viewing was unconstrained in the study by Hubbard (1995), one may again assume that observers pursued the target with their eyes. However, the quality of pursuit depends on how many objects are presented on the screen. When there is only one object, one may safely assume that the observer follows the target with the eyes. With each additional element, smooth pursuit degrades, and it becomes more probable that observers decide to fixate a nontarget, stationary element instead. Because the overshooting of the eyes’ motion after the disappearance of the target depends on pursuit eye movements, a reduction of pursuit will also reduce forward displacement. Consistent with this explanation, the effect of a surface on forward displacement was easily be changed by instructing observers to either look at the surface or at the target (Kerzel, 2002). Thus, the eye movements produced by multiple objects presented along with the target, rather than representational friction, explain why an additional surface reduces the forward error.

EFFECTS OF TASK TYPE: POINTING VERSUS PERCEPTUAL JUDGMENT

So far, we have seen that forward displacement with implied motion occurs in the absence of eye movements, whereas forward displacement with smooth motion depends on the execution of pursuit eye movements. However, at least one study in which eye fixation was monitored reported forward displacement with smooth motion (Müsseler, Stork, & Kerzel, 2002). It is noteworthy that subjects in this study indicated the final target position by moving a mouse cursor, as in Hubbard’s studies. Moving the mouse may be considered a form of pointing response in which movements of the hand are transformed into coordinates on the screen. These motor responses have to be contrasted with purely perceptual responses that only require a symbolic or verbal response. In the studies of Freyd, for instance, observers were asked to press buttons indicating whether or not they thought that the probe rectangle was in the same position as the third target rectangle. In this case, the mapping between motor response and meaning was arbitrary, and may just as well have been replaced by a nonspatial response (e.g., saying “yes” or “no”).

Why should the response mode matter? An influential neurophysiological theory (Goodale & Milner, 1992) holds that visual information for motor responses (e.g., pointing) is processed in a different area of the brain than visual information for conscious perception (e.g., saying where a stimulus is, relative to another). To investigate whether task demands affect localization of the final target position, Gegenfurtner and I (Kerzel & Gegenfurtner, 2003) asked observers in one condition to point to the final position of a smoothly moving target on a touch screen and those in another condition to compare the final target position to the position of a probe stimulus appearing some time after disappearance of the target (see Fig. 4).

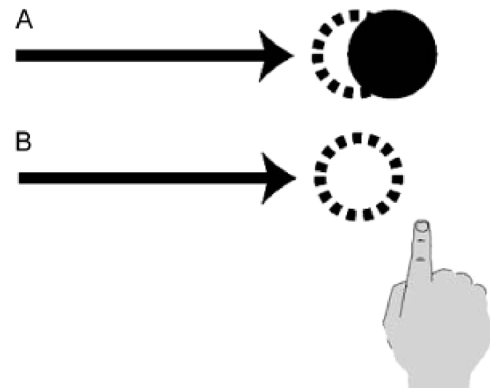

Fig. 4. Different methods to indicate the location of an object on a computer screen. To localize the final position of a moving target (dashed circle), observers may be asked to compare the remembered final position to the position of a probe stimulus (black circle in A). The resulting response is of symbolic nature (‘‘same–different’’ or ‘‘ahead–behind’’). Alternatively, observers may be asked to directly point to the final target position (B). In the latter case, the deviation between the endpoint of the movement and the true position is registered by a touch-sensitive screen. A mouse cursor may also be employed to point to the final target position.

Consistent with the idea of separate processing for perception and action, the amount of displacement differed between the two conditions. With probe judgments, there was no forward displacement, a result that replicates previous studies. In contrast, the endpoints of pointing movements were displaced in the direction of motion. A similar result was obtained for mouse pointing (Kerzel, 2003b). Thus, two factors may have increased forward displacement in Hubbard’s paradigm: unconstrained viewing and a motor measure of displacement.

FUNCTIONAL CONSIDERATIONS

As outlined at the beginning, errors in human performance give hints about the operation of the cognitive system. Initially, it was proposed that a uniform ensemble of mechanisms, internalized physical laws, gives rise to distortions in visual short-term memory. The studies outlined above show that mental extrapolation of the next target position, smooth-pursuit eye movements, and motor prediction also contribute. What functions do these mechanisms serve? Mental extrapolation of the next position may help people to accurately intercept the position of objects that are temporarily hidden from view. This is often necessary in ball games, such as football, where the target object may be obscured by other players. Moving the attention toward where an occluded target is likely to reappear makes responses to such objects faster and more accurate. The error associated with smooth-pursuit eye movement results from the necessity to anticipate target motion. The eye moves beyond the final target position because the system has already planned future movements and their execution cannot be stopped when the target vanishes. Finally, the forward error observed in pointing movements may help to compensate for neuronal processing delays: It takes time (about 100 ms) to process visual information, so a target will have changed its physical position before a person consciously perceives it. Because perception lags behind, movements directed at the currently available position of moving objects would also lag behind. The visuomotor system may have solved this problem by pointing at positions slightly ahead of the target. Another idea is that perception itself has evolved a mechanism that extrapolates the trajectory of a moving object into the future (Nijhawan, 2002).

FUTURE DIRECTIONS

The present article suggests an ensemble of mechanisms explaining forward displacement. Clearly, some of the findings challenge an account in terms of internalized physical laws. Future research will be needed to show whether evidence for cognitive analogues of physical laws may be obtained while observer action (eye movements, response mode) is controlled for. One further avenue for future research is to investigate visual short-term memory in more naturalistic environments (e.g., Thornton & Hayes, 2004). After all, the visual system did not evolve to deal with impoverished displays consisting of a few dots or a rectangle. Thus, strategies used to anticipate the behavior of moving objects may become more evident. Also, the present work calls for more attention to knowledge that is embodied in the functionalities of our eyes or limbs: Even if participants fail on paper-and-pencil tests, observation of their actions may still reveal that they have internalized knowledge about the physical world. Similarly, students may more easily understand the abstract principles of dynamics if examples related to their own behavior are given. In the context of driving, it may be useful to highlight potential errors associated with mechanisms of extrapolation: Objects that suddenly stop or go out of sight may be mislocalized in the direction of motion. While this mislocalization may be helpful when the object's future trajectory has to be predicted, it may be harmful when the final position itself has to be avoided (e.g., a stopped car).

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