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EDITORIAL FOCUS

Towards a functional understanding of gaze in goal-directed action

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Humans have creatively invented many games and sports that require goal-directed action. We throw, kick, hit, push, or slide objects of all shapes and sizes, aiming to successfully interact with an object (e.g., catching a ball) or to project an object into a designated target area (e.g., making a free throw). In such action tasks, the allocation of gaze—or where we look—is closely linked to ongoing movement control. For example, when catching a ball, humans track the moving object with their eyes until they intercept it (1), and when making a free throw, the eyes remain on the hoop during the throw (2). Although every action task has different movement demands, gaze is often allocated in stereotypical ways, indicating a functional role for the acting system (3).

Fixating an object of interest or a designated target space provides central vision of action-relevant objects to the movement system. In addition, peripheral vision and gaze-related information, such as proprioceptive signals and efference copies of oculomotor commands, are available to support action control. Previous work on eye-hand coordination in everyday life has proposed several functions of gaze that are linked to sensory information processing (4). These functions include searching for visual information by localizing action-relevant objects, using sensorimotor information to direct the effector and guide contact between the actor and the environment, and uptaking information to confirm successful movement execution and valuate action outcome (Fig. 1).

Many goal-directed action tasks, such as making a sandwich, require the effector (e.g., the knife) to interact with the environment. Whereas fixating action-relevant objects (e.g., the peanut butter jar) facilitates searching for visual information, fixating the contact location (e.g., the knife on the sandwich) aids object manipulation (Fig. 1*B*). However, in some action tasks, such as in the British pub game *Skittles*, the object, rather than the actor, impacts the environment (Fig. 1*C*). Here, fixating the target space is largely decoupled from movement execution. In a recent study published in the Journal of Neurophysiology, Brand et al. (5) investigated the role of gaze and sensorimotor predictions in a goal-directed throwing task akin to the *Skittles* game. By describing the timing of gaze shifts following ball release and the duration of target fixations in the target space, the authors provide new insights about how visual information is used for error feedback processing.

In the *Skittles* task, participants rotated a metal lever to simulate pulling back a ball attached to a post, and released the ball by lifting their index finger from the manipulandum. On a computer screen, participants had a birdseye view of the starting position, the real-time position of the lever, the real-time position of the virtual ball, the stationary post, and the target. In this semi-virtual environment, participants aimed to hit a single stationary target. Once participants were proficient at the task (nearly 90% hit rate), visual feedback of the ball trajectory and action target were manipulated. In a subset of trials, the ball trajectory and target became invisible at the time of ball release, leaving participants with only internal information about their gaze shift to predict the target position (i.e., proprioceptive signals and efference copies of oculomotor commands). In another subset of trials, the ball trajectory also became invisible at the time of ball release, but the target remained visible, thereby acting as a salient visual object that participants were likely to fixate. In all trials, participants received feedback information about their throwing outcome 500 ms after the arrival of the ball in the target space.

Brand et al. (5) found that following ball release, participants predictively moved their eyes to the location where they estimated the ball to arrive, indicating that participants valuated whether the ball would hit or miss the target. Because these gaze shifts occurred after movement execution but before the ball hit or missed the target, the observed predictive gaze pattern was likely related to action outcome valuation rather than to action planning and execution. Moreover, the authors found predictive gaze shifts to future action effects irrespective of whether visual feedback of the ball trajectory and the target was given. In trials in which the ball flight and target were invisible, participants had to rely on internal sensorimotor information about their gaze shift to control visual information uptake. In contrast, the authors found that in trials in which the ball flight but not the target was invisible, participants moved their eyes to the actual (visible) target position, rather than the predicted ball location in the target space.

When sampling sensory information from the environment, it is not only important where gaze is allocated, but also how long relevant objects are fixated. How long an object is fixated in real-world action tasks is related to fixation

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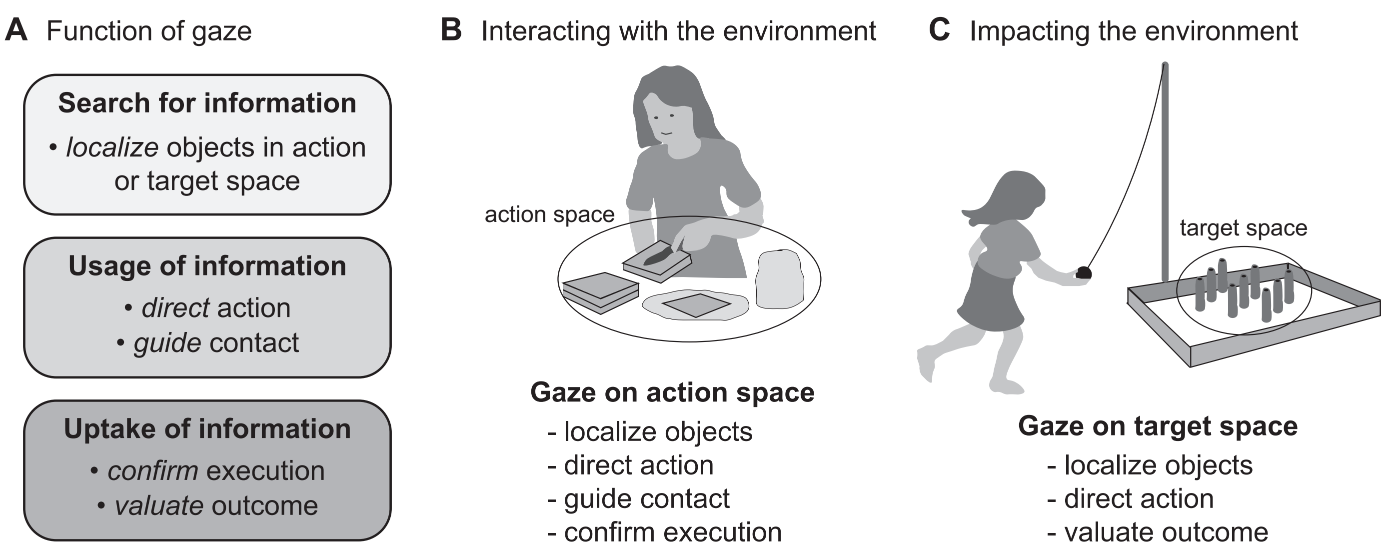

Figure 1. The function of gaze for an acting system. *A*: the allocation of gaze can be linked to the search for visual information, the use of sensorimotor information, and the uptake of sensory information. *B*: in action tasks, such as object manipulation, contacting the environment shapes the demands for gaze. *C*: in action tasks, such as target sports, the impact of the object on the environment shapes the demands for gaze.

dispersion (i.e., how wide gaze is cast), with fixations lasting longer in tasks that require smaller gaze shifts (6). Brand et al. (5) showed that participants fixated the target space longer in unsuccessful (miss) compared with successful (hit) trials, and that fixation duration was generally increased in trials in which the ball nearly hit or missed the target. These results indicate that—in addition to environmental constraints—the duration of valuation fixations depends on movement outcome, and that longer fixations may facilitate error feedback processing. These results also support the idea that continuously measuring the timing and sequence of gaze shifts in goal-directed action tasks can serve as a readout of sensorimotor decision-making and cognitive processes (7).

To understand natural behavior in neuroscience, we need to develop experimental tasks that mimic naturalistic movement constraints, but also allow the ability to control the experimental environment and yield interpretable results (8, 9). The work presented by Brand et al. (5) highlights that studying naturalistic action tasks can lead to a functional understanding of oculomotor control. The authors find stereotypical gaze patterns—that is, predictive gaze shifts to the estimated location of impact—irrespective of whether visual information of the ball flight was available. Future studies could further probe the mechanisms of sensorimotor prediction and the function of valuation fixations by either increasing the available sensory information (e.g., by adding multisensory input) or by degrading available sensory information (e.g., by adding noise to the environment). Whether and how the duration of valuation fixations is functionally related to action learning and/or error feedback processing could be probed by manipulating the validity and availability of the information about performance outcome.

The decision of when, where, and for how long to allocate gaze to is related to task-specific action goals that are embedded in the environment. Whether and how gaze has a functional role for information processing and action performance is not yet fully understood. Brand et al. (5) provide compelling evidence that sensorimotor predictions are important for visual information uptake that facilitates error feedback processing. However, in the real world, goal-directed action is rarely performed in isolation. For example, while playing a game of Skittles, one might also hold a drink in hand or chat with a group of friends. Thus, future research is needed to elucidate how visual information is searched for, used, and taken up when several tasks compete for gaze.

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AUTHOR CONTRIBUTIONS

J.F. prepared figures; N.H.I. and J.F. drafted manuscript; N.H.I. and J.F. edited and revised manuscript; N.H.I. and J.F. approved final version of manuscript.

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