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Guiding Movements by Constantly Reconsidering One's Actions: A Kinematic Approach

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Abstract

People have to deal with a lot of uncertainty in their daily actions. This uncertainty arises from the limited resolution of their sensory processing and motor control, as well as from unpredictable changes in the environment. How do people ensure that their actions are successful when faced with all this uncertainty? We argue that they do so by constantly reconsidering their plan in accordance with their instantaneous evaluation of the circumstances. Doing so allows them to quickly respond to any changes in the environment. The response can be a small adjustment to an ongoing movement, but also diverting the movement if it suddenly becomes evident that moving toward a completely different target is more suitable for some reason. We present a simple kinematic model based on the idea that it is always beneficial to move smoothly to illustrate how continuously reconsidering movement plans can explain many findings in the literature.

INTRODUCTION

People walk around and pick up objects so effortlessly that doing so seems simple, but it is not. When reaching out for an object, one must move one's hand to where the object will be at the moment that one expects to grasp it. But one has to deal with a lot of uncertainty to actually arrive at the right place. Some uncertainty stems from the environment. Someone handing you an object might make an unexpected movement, or someone else might move their hand into the path you intended to take. When trying to catch a ball, its path could be changed by the wind, or it might bounce in an unexpected direction because it hit a small stone.

Another source of uncertainty arises from limitations in how precisely one can judge the position and motion of an object that one is reaching out for, one's own posture, and changes in one's own posture. The retinal resolution at the fovea can be very high (Wang & Levi 1994), so the difference in direction between two visible objects that are close to each other can be judged very precisely if one directs one's gaze toward them. But the retinal distance between the target and a representation of the hand does not appear to be used to guide human movements (Brenner & Smeets 2003; Crowe et al. 2021a,b; Franklin et al. 2016). Various other kinds of information are used instead (Brenner & Smeets 2022b). Such information often involves judging the distance to the object (Brenner & Smeets 2018b), the orientation of one's eyes (Bridgeman & Stark 1991), and other aspects of one's posture (Kuling et al. 2016), all of which are judged with limited precision.

Many of the relevant judgments are ones with respect to the observer (Colby 1998; Crowe et al. 2021a,b; Desmurget et al. 1998), so they continuously change as the observer moves. There is an extensive literature on how observers consider changes in their viewpoints (Fiehler & Karimpur 2023, Harris et al. 2000, Warren & Rushton 2009) and directions of gaze (Klier & Angelaki 2008, Medendorp et al. 2003, Van Pelt & Medendorp 2007) when making all kinds of visual judgments, but the fact that people look at objects as they reach out for them (Land & Hayhoe 2001) suggests that it is important to constantly obtain new information. Indeed, when judging objects' positions, people continuously replace outdated information with new information (Brenner et al. 2023). They also appear to rely on the latest information about the moving hand (Brenner & Smeets 2023; Saunders & Knill 2003, 2004, 2005), even if gaze is not directed at the hand (Cámara et al. 2018).

In the next sections, we review the literature on visual guidance of goal-directed movements from the perspective that one must deal with a lot of uncertainty. We first briefly discuss delays, because a critical aspect of our proposal is that people try to rely on the latest information, and it is only useful to consider the latest information if such information is not too outdated. We then discuss why we believe that the latest information is used to evaluate the best option at each moment. Then, we present a simple way to simulate movements that are constantly guided by the latest information. Finally, we show how the simple kinematic simulation can reproduce many experimental findings: the asymmetry in the velocity profiles of visually guided goal-directed arm movements, the influence that removing visual information has on the precision of movement endpoints, the speed–accuracy tradeoff, responses to perturbations, and the consideration of instantaneous circumstances when making choices.

DELAYS

How long it takes visual information to influence goal-directed arm movements was initially estimated by determining how long such movements have to take for vision to make a difference (Woodworth 1899), how long one could occlude the hand on its way to the target before doing so influenced performance (Carlton 1981), and how soon after an occluded hand reappeared the hand's movement was adjusted (Carlton 1981). More reliable estimates of the delay were obtained by determining when the arm responded to a sudden displacement of the visual target (Brenner & Smeets 1997, Georgopoulos et al. 1981, Prablanc & Martin 1992, Sarlegna & Mutha 2015, Van Sonderen et al. 1989) or of a representation of the hand (Brenner & Smeets 2023; Dimitriou et al. 2013; Sarlegna et al. 2003; Saunders & Knill 2003, 2004, 2005). The estimated delay is usually 100 ms or slightly more.

Systematically varying the properties of the target revealed that the delay in responding depends on many experimental details, such as the contrast between the target and its surroundings (Veerman et al. 2008). Even if people constantly update their plans according to what they know about the circumstances at that moment, since different kinds of information take different amounts of time to process, the information that is used will have originated at different moments. Consequently, if several sources provide similar information, the information with the shortest delay is likely to influence performance the most (van Mierlo et al. 2009). If different sources suggest that one take different actions, performance will be influenced by them sequentially. Thus, if the task is to stop moving if the target's position changes, the movement toward that target might temporarily be guided toward the new position of the target before it can be inhibited as a result of the change itself being detected (Pisella et al. 2000). Due to the delay between light reaching the eye and muscle contractions moving the arm, any response is always based on slightly outdated information, but at each moment the action can be determined by the latest information about the situation. We mainly discuss visual information and responses to visual information, but, of course, similar reasoning applies to other modalities.

CONSTANTLY EVALUATING THE BEST OPTION

Is there more to the distinction between planning an action and executing it than that planning occurs before movement onset and execution occurs after movement onset? Is more information used to plan the action? Are more options considered? New information about the positions of the target and the hand is used to guide movements, and some of the pathways that might be involved have been identified (Stein & Glickstein 1992). Always considering the latest positions of the target and the hand could mitigate errors arising from sensory or motor imprecision or biases, as well as errors arising from changes in the environment (Brenner & Smeets 2018a). But what about other kinds of information? Can all relevant information be used to guide an ongoing movement if there is enough time to use such information?

A reason to suspect that all information that can be used before the movement starts can also be used during the movement is that it does not necessarily take longer to divert an ongoing movement toward a new target than to adjust the movement toward the original target (Brenner & Smeets 2015b, 2022a; Gallivan et al. 2018). Moreover, the position of the hand is considered when choosing whether or not to move toward a different target (Brenner & Smeets 2015b, 2022a; Nashed et al. 2012). The position of the hand is also considered when selecting between potential targets (Brenner & Smeets 2022a, Hadjipanayi et al. 2023). The hand's position is even considered if the hand is perturbed mechanically (Nashed et al. 2012) or by moving the background 100 ms before a choice had to be made (Hadjipanayi et al. 2023).

An implication of constantly reconsidering the whole movement is that one will not compensate for deviations from the originally planned movement if such deviations do not interfere with achieving one's goal (Todorov & Jordan 2002). This can explain why there is more variability in aspects of movements that do not interfere with achieving the goal than in ones that do (Scholz et al. 2000, van Beers et al. 2013), because random fluctuations in how the movement unfolds will lead to new suitable endpoints being selected as long as the new endpoint is consistent with achieving one's goal. Similarly, it explains why people compensate less vigorously for mechanical perturbations if the perturbed movement will still reach the target (Nashed et al. 2012), because it is the new situation that is considered, not the perturbation. People readily follow a different movement trajectory when the ongoing movement is mechanically perturbed as long as doing so does not interfere with the goal of the action.

Aspects of movement adjustments that have been studied are generally consistent with the idea that the best course of action is selected at each moment. For instance, when a target's position suddenly changes, the vigor with which the movement is adjusted depends not only on whether an adjustment needs to be made but also on the remaining time (Brenner et al. 2023, Česonis & Franklin 2020, Oostwoud Wijdenes et al. 2011) and the anticipated additional variability that adjusting the movement is likely to introduce (Liu & Todorov 2007). One might worry that constantly determining the most suitable way to proceed with one's action on the basis of the latest information, ignoring what was considered to be the most suitable way to proceed a split second ago, would lead to constant switching between options, but if one is moving toward one of several targets, the direction in which one is moving will usually make that target the best option (Brenner & Smeets 2022a). Therefore, constantly updating the plan mainly provides the flexibility to pick a different endpoint if the movement is mechanically perturbed (Nashed et al. 2012) or if a better option appears (Brenner & Smeets 2015b).

SIMULATIONS

The idea of constantly reconsidering the whole action might sound complicated and therefore difficult to test. To show that many reported findings could be accounted for by a few simple assumptions if we follow this idea, we perform some simple simulations. For the simulations, we assume that it is beneficial to move smoothly, that there is a delay of 100 ms in responding to (visual) information, and that both visual judgments and motor performance are noisy. We assume that all options are considered simultaneously, so that the best option is selected at each moment. To simplify matters, we only consider targets that are so small that one aims for their centers. In principle, following this idea, selecting a different position on a target is no different from selecting a different target.

Following the reasoning of Hogan (1984) and Hoff & Arbib (1992), we assume that movements are planned to be as smooth as possible and therefore to follow a fifth order polynomial with the constraints that the target should cover a certain distance within a given time. This assumption has been used to model various kinds of movements quite successfully (Fligge et al. 2012, Smeets & Brenner 1999, Viviani & Flash 1995). It has also successfully been used to model changes in trajectories in response to target perturbations (Flash & Henis 1991, Smeets et al. 2002). But in our simulations, the trajectory is constantly replanned, not only in response to perturbations. During the whole movement, we use the latest-available information to determine how to obtain the smoothest possible further motion [more or less following the abort and replan scheme of Flash & Henis (1991)]. The outcome of doing so determines how the movement is accelerated at that moment. In the simulations, we approximate continuous control by determining how the movement should proceed in time steps of 1 ms. At each moment, we determine the acceleration that would move the hand to the target as smoothly as possible given the available information at that moment. Considering a delay of 100 ms, the calculations rely on information that was available 100 ms earlier.

Thus, at each step we determine the acceleration that would be needed to move the hand to the target as smoothly as possible in the remaining time [using the equations of Hogan (1984)]. We introduce the delay by combining the simulated position and velocity 100 ms earlier with the planned acceleration during those 100 ms to obtain predictions of the present position and velocity. Taking these predictions as the initial position and velocity for the next step, and the last planned acceleration as the initial acceleration for the next step, and assuming that one reaches the target in the remaining time with a final velocity and acceleration of zero, together allows us to determine the next acceleration. This acceleration is used to update the simulated velocity in the next step, and the simulated velocity is used to update the simulated position (and thereby the remaining distance). Planning the movement to have a final velocity and acceleration of zero is representative of movements that are stopped by the participant rather than by the target. At the very start of the simulated movement, the hand is static (its velocity is zero), but in some cases, we use a nonzero acceleration to produce an asymmetrical velocity profile. If the position and motion of the hand are judged correctly and the hand follows the calculated acceleration, this simulation is just a more complicated way to obtain the conventional minimal jerk trajectory. But this way of simulating movements allows us to consider variability in sensory judgments and in executing the movement.

To what extent does continuously adjusting the acceleration of the hand in this manner give rise to known characteristics of human movements? In particular, how do the simulations behave when faced with sensory and motor noise and sudden changes in the target's position? We consider two sources of random errors. One is misjudging the distance between the hand and the target, which is used to calculate the acceleration for updating the movement. The other is noise in the produced acceleration of the hand, which is only added to the planned acceleration when updating the movement, so it can only be compensated for after 100 ms, when its influence becomes apparent in the simulated target velocity and displacement. Each of these sources of random errors is implemented by adding random variability drawn from a normal distribution with a standard deviation of 20% of the current value: the remaining distance to the target or the acceleration of the hand (a negative distance to the target is interpreted as having overshot the target). New values were selected at every step (i.e., every millisecond) except when simulating occlusion of vision. The variability was chosen to be proportional to the magnitude because variability in distance judgments is known to increase with the distance itself (Whitaker & Latham 1997), and movement variability is known to scale with movement vigor (Schmidt et al. 1979).

When vision is occluded, the judged position of the target is no longer updated, so the hand can no longer be guided by the actual change in distance. It therefore has to be guided by predictions of the change in distance from the time of the occlusion (considering the random error at that time) rather than being guided by predictions only for 100 ms (considering the constantly changing random errors). Considering positions 100 ms earlier means that when a target is suddenly displaced, its position after the displacement is used to calculate the required acceleration 100 ms later. We are not claiming that human movements are always planned in a manner that minimizes jerk in this manner, that these are the only two sources of error, or that 20% variability every millisecond is representative in any way. This is just a simple way of simulating smooth movements that are adjusted when faced with external perturbations (i.e., target shifts) and internal uncertainty (i.e., sensory or motor noise). As we show in the following sections, this simple kinematic model captures many of the observed characteristics of human goal-directed movements, which supports the credibility of the underlying proposal that movements are constantly reconsidered. Details of the simulations can be found in the python script minJerk.py at **https://osf.io/7bkvj/**.

VELOCITY PROFILES

A fundamental finding in goal-directed movements is that slow movements are more precise than fast ones (Fitts & Peterson 1964). This could be explained by signal-dependent noise in the commands that govern the acceleration of the hand (Harris & Wolpert 1998), which in the absence of

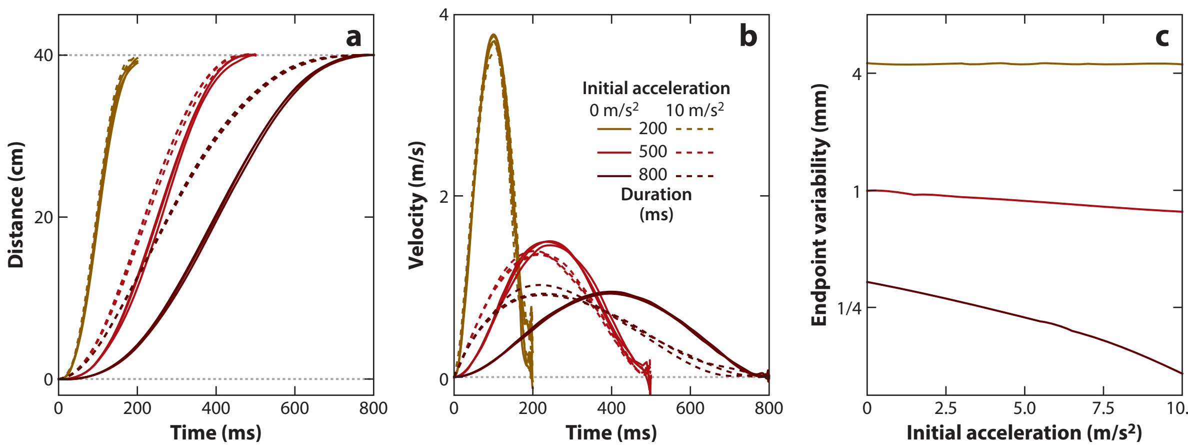

Figure 1

Simulated movements. (*a*) Displacement as a function of time for 40 cm movements performed in 200, 500, or 800 ms. For each duration, there are three simulated movements starting with no acceleration (*solid lines*) and three with an initial acceleration of 10 m/s^2 (*dashed lines*). (*b*) Velocity as a function of time for a similar set of movements. Note the asymmetry in the velocity profile for slower movements with a nonzero initial acceleration. (*c*) How the standard deviation of the endpoints of 10,000 simulations depends on the initial acceleration for each movement duration. Note the logarithmic scale of the variability axis.

any adjustments could lead to the variability of the executed movement being proportional to its speed. But the velocity profile of slow movements is often skewed, starting fast and then slowing down (MacKenzie et al. 1987), presumably to improve precision by allowing adjustments to the ongoing movement on the basis of new information to be made while the hand is close to the target and moving slowly (Elliott et al. 1999). **Figure 1*a*** shows simulated movements that cover a distance of 40 cm in 200, 500, or 800 ms. As already mentioned, the planned simulated movements start and end with a velocity of zero. They end with an acceleration of zero, but they can start with a positive acceleration to allow the velocity profile to be asymmetrical. We show simulations for initial accelerations of 0 and 10 m/s^2.

The velocity profiles of our simulations (**Figure 1*b***) look similar to those of measured data and to those of regular minimal jerk trajectories (with no added noise or continuous consideration of the latest-available information), confirming that our continuous version of simulated minimal jerk movements performs as expected when there is no perturbation, despite the added variability. The extent of the asymmetry can be manipulated by adjusting the initial acceleration. In our simulations, the asymmetry is larger for slower movements because we did not scale the initial acceleration with movement speed. We did not do so because there is a maximal acceleration that people can achieve when performing such tasks (Brenner et al. 2023). There are some excessive changes in velocity at the very end of the movement that are not observed in human movements. Presumably any attempt to actually move so abruptly would be removed due to limitations on the acceleration (i.e., biomechanical damping).

Examining how the endpoint errors depend on movement speed (curves in **Figure 1*c***) and on the initial acceleration (horizontal axis in **Figure 1*c***) shows that increasing the movement time, and in particular doing so near the end of the movement, improves performance (i.e., reduces the variability in the endpoints). Thus, the advantage of having a skewed velocity profile, especially for slow movements, follows naturally from our simulations. That slower movements are more precise than fast ones is hardly surprising. We return to this in more detail in the section titled Speed–Accuracy Tradeoff. Showing that an asymmetrical velocity profile leads to greater precision in the endpoints (the curves in **Figure 1*c*** have a negative slope) can explain why people tend to move in this manner, despite this requiring a larger initial acceleration (so more jerk at the very beginning of the movement).

REMOVING VISUAL INFORMATION

Movements are not only less precise and less accurate when performed without visual guidance but also less asymmetrical (Woodworth 1899). They are also less precise, less accurate, and less asymmetrical when moving fast (Soechting 1984). To simulate moving at different speeds with vision removed at various times, we assume that judgments of the distance to the target stop being updated on the basis of new visual information once vision is removed. This means that the planned acceleration follows the calculated minimal jerk trajectory from then on, but the actual acceleration is influenced by the additional variability of 20% of the planned acceleration at each moment. The actual acceleration determines how the velocity, and thereby also the position, changes with each step. Not considering the latest position and velocity of the hand increases the endpoint variability because early errors are not corrected. In addition, not updating the judged distance results in larger errors when vision is removed early in the movement because the error in judging the distance is proportional to the distance itself.

Simulating the anticipated variability when vision is removed at various distances from the target shows that removing vision is particularly detrimental for slow movements (red curves in **Figure 2*a***). Removing vision during the last 100 ms of the movement obviously does not influence performance (values beyond the rightmost symbols in **Figure 2*a***). **Figure 2*a*** shows that for a given movement duration, having an asymmetrical velocity profile is only advantageous if vision is available throughout the movement (dashed lines with open symbols are only below the corresponding solid lines at the very right of **Figure 2*a***). This is consistent with movements having asymmetrical velocity profiles in order to make use of visual information when moving slowly near the target. Therefore, the reason that movements have less asymmetrical velocity profiles when performed without visual guidance (Elliott et al. 1999) is probably that the asymmetrical velocity profile has no advantage, while starting with a strong acceleration might be costly (the initial jerk requires an abrupt change in muscle activity).

According to the simulations, moving more slowly does not reduce the endpoint variability unless visual guidance is available for most of the trajectory. That is consistent with it hardly being advantageous to move slowly when moving without visual guidance (Woodworth 1899). In this context, it is worth noting that in real movements, removing vision is much less detrimental than is suggested by our simulations. Removing vision early in the movement only doubled the standard deviation of the endpoints in a study by Ma-Wyatt & McKee (2007). But in that study, the target was no longer visible during the movement, even when vision was not removed, which probably reduced the effect. Woodworth (1899) found a slightly larger advantage for slow movements but nowhere near the differences that we find. Thus, our simulations of removing visibility overestimate how detrimental doing so really is. This is probably because we assume that no new information whatsoever is available after that time, which is probably not true.

The position of the target must indeed be determined visually, unless one is moving the hand to a target that one is holding in the other hand (Camponogara & Volcic 2019a,b). When repeating the same movement, one might also remember the felt position of one's hand at the end of the previous movement, but using such information is unlikely to make movements much more precise. However, the position and velocity of the hand are normally determined both haptically and visually (Desmurget et al. 1998). In the simulations, we assume that no new information is used from the moment that the hand is hidden from view. But in real movements, the position

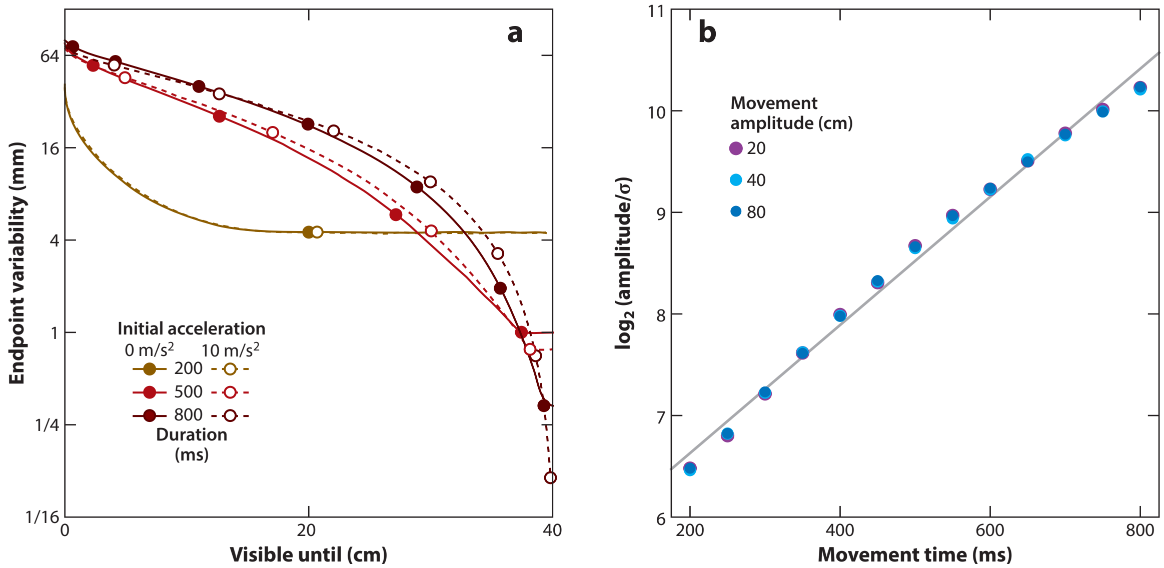

Figure 2

Reduced precision of goal-directed movements if vision is occluded or one moves fast. (*a*) Variability in the endpoints of simulated 40 cm movements when visual guidance stops once the movement has reached a certain distance. The absence of guidance is modeled by predicting the acceleration for the remaining time on the basis of the last visually judged distance (with its error at that moment) and the velocity and acceleration at the moment that visibility is removed but still adding random variability to the acceleration of the hand. The dots separate 100 ms intervals, indicating approximately when the distance at which vision is removed has been reached. (*b*) The simulated movements have a realistic speed–accuracy tradeoff, with an (almost) linear relationship between the logarithm of the precision and the movement time, where precision is defined as the movement amplitude divided by the endpoint variability (i.e., the reciprocal of the standard deviation in the endpoints as a function of the distance to the target).

and velocity of the hand could keep being updated on the basis of haptic information. Relying on haptics alone rather than both haptics and vision will undoubtedly give a less precise estimate of the velocity of the hand and of the remaining distance at each moment. But maintaining the corrections in the simulations, just with more variability in the velocity of the hand and the remaining distance, will give a more modest increase in the variability of the endpoints. Moreover, in that case, moving slowly would reduce the variability, even without vision, rather than increase the variability, as it does in our simulations (left side of **Figure 2*a***).

SPEED–ACCURACY TRADEOFF

The relationship between speed and accuracy has been studied very extensively for human goal-directed arm movements (Fitts & Peterson 1964, Meyer et al. 1982, Plamondon & Alimi 1997). The classical method to study this relationship is by varying task difficulty and measuring movement time (Fitts & Peterson 1964). Since we have to specify the movement time when simulating movements, we relate endpoint variability (in relation to movement amplitude) to the movement time (Schmidt et al. 1979) rather than the movement time to the required precision. We find the expected, almost linear relationship between movement time and the logarithm of target distance divided by endpoint variability (**Figure 2*b***). However, the slope is about half as steep as that found by Fitts & Peterson (1964). Part of this difference may be that we simulated symmetrical movements (i.e., movements with an initial acceleration of zero). If the initial acceleration is higher, the slope is slightly higher, but not twice as high. Maybe this difference is due to our rather arbitrarily selected sources and magnitudes of variability. That the simulations do not reproduce human movements quantitatively correctly can also be seen in **Figures 1*c*** and **2*a***, where asymmetrical movements (i.e., ones with a large initial acceleration) with a duration of 800 ms have an endpoint variability of about 0.1 mm. The unrealistically large changes in velocity near the end of the simulated movements (**Figure 1*b***) likely correct a larger part of the error in the simulated movements than can be corrected in real movements, and we have probably underestimated the magnitude of the instantaneous sensory and motor errors.

RESPONDING TO PERTURBATIONS

Much of what we know about guiding movements stems from experiments in which the visual information was perturbed and the response to such perturbations was evaluated. A groundbreaking perturbation study examined how the unseen hand responded to an undetected change in target position (Goodale et al. 1986, later replicated by Prablanc & Martin 1992). The target was visible while the hand was not, because the target was seen via a mirror while the hand moved behind the mirror. The change in target position was not detected because it occurred during a saccade. Despite not having seen the target move and not seeing their hand, the participants' movements were quickly adjusted such that they would reach the new target position. This is consistent with the idea that the movement is guided to the target by the information that is available at each instant, so there is no need to detect the change.

Figure 3 shows simulated responses to typical target perturbations. Similar responses are seen in human movements (Brenner & Smeets 1997, 2023; Liu & Todorov 2007). In accordance with empirical observations (Brenner et al. 2023, Brenner & Smeets 2023, Oostwoud Wijdenes et al. 2011), the response is adjusted to the remaining movement time: It is more vigorous if the perturbation occurs later in the movement. Responses to perturbations have mainly been studied

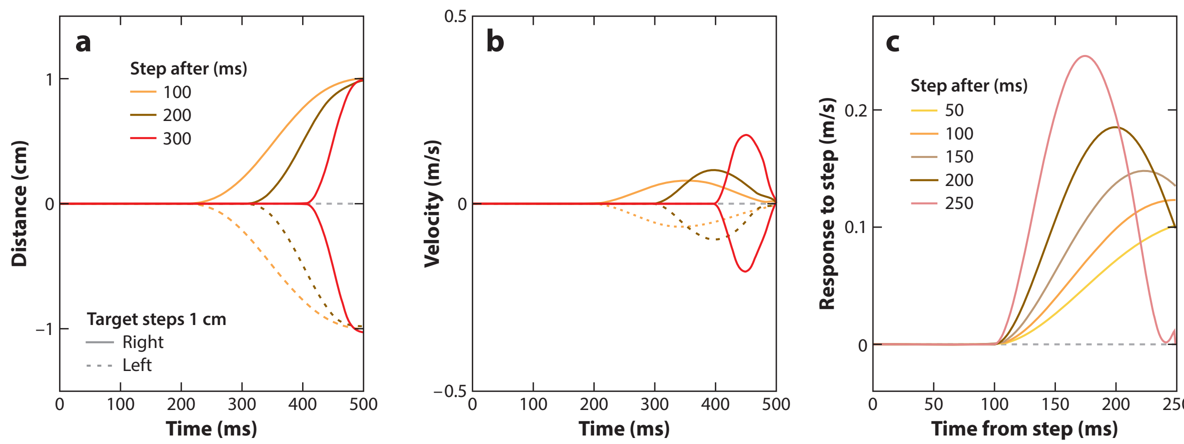

Figure 3

Simulated responses to the target abruptly stepping 1 cm away from the main movement direction. (*a*) Distance from the main movement direction as a function of time for steps at different moments. Solid and dashed lines represent steps to the right (positive) and left (negative) with respect to the movement direction, respectively. The response starts 100 ms after the step due to the 100 ms delay. (*b*) Corresponding velocity profiles. The colors and solid versus dashed lines are the same as in panel *a*. (*c*) The response to the step can be quantified as the average difference in velocity between trials on which the target stepped to the right and to the left. By showing this as a function of the time from the moment of the step, we can clearly see the vigor of the response increasing and its duration decreasing as the movement progresses (later steps). This is precisely what is observed in human responses (Brenner et al. 2023). Panels *a* and *b* show individual trials. Panel *c* shows the average of 10,000 trials for each condition.

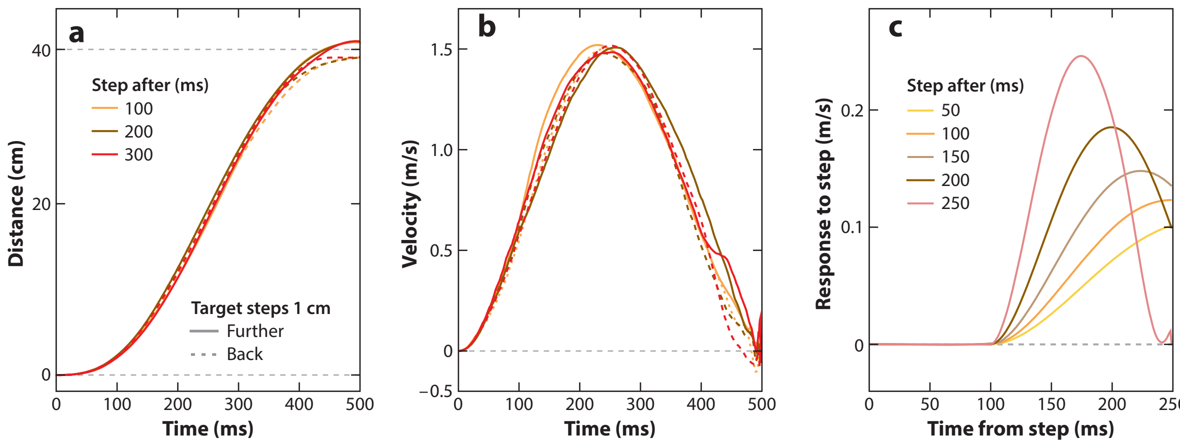

Figure 4

Simulated responses to the target abruptly stepping 1 cm along the main movement direction. (*a*) Distance along the main movement direction as a function of time for steps at different moments. Solid and dashed lines represent the target stepping further or back along the movement direction, respectively. (*b*) Corresponding velocity profiles. (*c*) The average difference in velocity between trials on which the target stepped further and back. Panels *a* and *b* show individual trials. Panel *c* shows the average of 10,000 trials for each condition.

for changes in direction (as simulated in **Figure 3**). The reason for this is mainly that it is easier to isolate the response to perturbations when the response is orthogonal to the main movement direction. The actual responses to perturbations of distance and direction are similar (Oostwoud Wijdenes et al. 2013). And, indeed, although simulated responses to target perturbations along the movement direction are less conspicuous when looking at individual trials (compare **Figures 3*a*** and **4*a*** or **Figures 3*b*** and **4*b***), they are actually extremely similar if you average enough data (compare **Figures 3*c*** and **4*c***).

Another perturbation that has frequently been used is background motion. Moving the background has been shown to influence the perceived position of a static target (Brenner & Smeets 1997). Sudden onset of background motion also influences goal-directed arm movements (Brenner & Smeets 1997, Saijo et al. 2005). The movements are influenced by any motion close to their anticipated endpoints (Crowe et al. 2021c) or where gaze is directed (Abekawa & Gomi 2010). Often the two will be the same, but that is not always the case. The response appears to depend on gaze rather than the anticipated endpoint when moving toward the remembered position of a static target that was removed before the background started moving (Abekawa & Gomi 2010). But the response appears to depend on where the target will be hit rather than where gaze is directed if the target is moving and remains visible (Brenner & Smeets 2015a). The vigor of the response is larger if the background moves faster (Gomi et al. 2006) or later during the movement (Crowe et al. 2022). It does not depend on the spatial frequency or luminance contrast of the background (unless the contrast is less than 10%; Gomi et al. 2006) or the background's temporal stability before it starts moving, or whether it is a different color than the target (Crowe et al. 2021c). These findings can likely be explained by the planned movement endpoint (temporarily) being pulled in the direction of the background motion.

Responses to changes in target velocity are much more difficult to study, because if a target changes velocity, its position also changes at a different rate. Nevertheless, there is some evidence that changes to the target's velocity are considered when guiding arm movements. When intercepting targets that move in the frontal plane, the direction in which the hand moves depends systematically on the target's position, but the velocity with which the hand moves is primarily influenced by the target's speed (Smeets & Brenner 1995). The reason that the hand's speed depends on that of the target is presumably that moving faster helps one get the timing right (Brouwer et al. 2000), probably because any error in judging the distance to the target will result in a smaller timing error if one is moving faster near the moment of impact (Brenner et al. 2012). It has been shown that when a target suddenly changes speed, not only does the hand aim for a different position, but the speed at which it moves also changes to match the new target speed (Brenner et al. 1998). This is what one would expect if how fast one can best move near the time of contact is constantly reconsidered or if both when and where to reach the target is reconsidered. The error that is made when target velocity is misjudged also suggests that the target's position is constantly reconsidered, because if motion of texture within a target makes the target appear to move faster or slower than it really is, people make errors that are consistent with them using the misperceived velocity to predict the target's displacement during the last 100 ms (de la Malla et al. 2018). While the latest target position always appears to be considered for guiding movements, the velocity that is considered is acquired over an extensive time period (Brenner et al. 2023), making it more difficult to interpret responses to changes in target velocity.

Our simulations and most perturbation studies only consider the need to reach the target (e.g., Brenner et al. 2023, Tresilian & Plooy 2006). Sometimes, how one reaches the target is also relevant. One might want to hit a ball such that an opponent cannot catch it, or to grasp a cup in a way that makes it easy to rotate the cup. A simple example is sliding one's finger along a surface to intercept a moving elongated bar. If the bar is small enough for there to be a danger of missing it, it can be advantageous to move along a trajectory that approaches the bar orthogonal to its longer side. Indeed, people do so. And if such a bar suddenly changes orientation, the hand's path changes accordingly (Brenner & Smeets 2009). This could obviously be simulated by choosing different constraints for the end of the movement, such as a simulated final acceleration that is not zero (Smeets & Brenner 1999). If an object that one is aiming to grasp rotates, the grip orientation changes accordingly (Chen & Saunders 2015, Desmurget et al. 1996). If a sphere rotates, the hand initially follows the rotation, but some time later the grip returns to its original orientation (Voudouris et al. 2013). This suggests that choosing different endpoints for the digits takes more time than adjusting the digits' movements toward the original endpoints. Thus, more than only reaching the planned endpoint is considered throughout the movement.

If the size of an object that one is reaching for changes, the grip aperture changes accordingly (Hesse & Franz 2009). If people are free to either grasp the object between finger and thumb or grasp it with their whole hand, the kind of grasp can also change (Bennett & Castiello 1995, Castiello et al. 1993). The grip aperture can also change if the object's shape changes (Ansuini et al. 2007, Chen & Saunders 2015, Eloka & Franz 2011). As is the case for tapping on moving targets, changes in grip aperture are more vigorous if the changes occur later during the movement (Hesse & Franz 2009). But responses to changes in target size appear to have longer latencies than responses to changes in target position (Paulignan et al. 1991). Moreover, they have been reported to take longer when both the position and the size change simultaneously (Castiello et al. 1998). This delay is probably caused by having to consider multiple aspects of the movement, because it is not found when simply tapping on targets (Brenner & Smeets 2022a). Responses to target shifts are found not only when the hand itself is moved toward the target but also when throwing balls at a target (Urbin 2013). In that case, the adjustment must obviously be made before the ball is released. Thus, we again see that many aspects of movements are reconsidered during the movement, but that delays may differ for considering different issues.

Another issue that one might need to consider when making goal-directed movements is obstacles. While many experimental studies are set up to avoid having obstacles, in daily life we often need to consider obstacles. For instance, when reaching for things on the table at mealtimes, there are usually many other items on the table besides the one you want. We know that people avoid obstacles (Dean & Brüwer 1994, Sabes & Jordan 1997), including ones that constrain their posture rather than the path of their digits (Vaughan et al. 2001, Voudouris et al. 2012). When the movement is perturbed mechanically, obstacle positions are considered when determining the response that will bring the hand back to the target (Nashed et al. 2012). When a target's position is perturbed, obstacle positions at the moment of the perturbation are considered when responding to the perturbation, even if they too are displaced at that moment: For identical initial obstacle positions, the response is different if the obstacles move to different positions at the moment that the target perturbation occurs (Crowe et al. 2023).

We already mentioned that movements are adjusted when a visual representation of the hand is perturbed (Brenner & Smeets 2023; Sarlegna et al. 2003; Saunders & Knill 2003, 2004, 2005). When using a computer mouse to guide a cursor across a screen, there is quite a complicated relationship between the felt position and motion of the hand and the position and motion of its visual representation, but how the hand responds to perturbations appears to be quite similar (Brenner & Smeets 2003). The response to target displacements has been reported to be faster when a representation of the hand is visible (Reichenbach et al. 2009), but the responses to target and cursor displacements differ, so people are not simply responding to the change in relative position (Brenner & Smeets 2003; Crowe et al. 2021a,b; Franklin et al. 2016). The response was more vigorous for narrower targets for which a more vigorous response was required if one was to reach the target (Knill et al. 2011). Thus, all in all, a lot appears to be considered during the movement, which supports the idea that the whole movement is reconsidered all the time.

CONSIDERING THE INSTANTANEOUS SITUATION

In perturbation studies, participants are usually expected to complete the ongoing action. We have seen that people correct less if there is less need to correct (De Comite et al. 2021, Knill et al. 2011) or if correcting less is advantageous (Liu & Todorov 2007). We have also seen that they move toward different endpoints on the object if doing so results in a more comfortable posture (Voudouris et al. 2013). When moving to one of several potential targets while avoiding obstacles, a mechanical perturbation could make the movement take a different path with respect to the obstacles or even make the movement end on a different target (Nashed et al. 2014). Nashed et al. (2014) interpreted this in terms of people planning several options and quickly selecting the best option, but it can also be interpreted in terms of constantly reconsidering the options. Finding that people do not fully adjust their movements to compensate for mechanical perturbations if doing so is not essential for achieving the task goal has been described in terms of a minimal intervention principle (Todorov & Jordan 2002), whereby the influence of the perturbation on the movement endpoint is accepted rather than compensated for as long as reaching the new endpoint is consistent with the goal of the action. It is a small step from this view of considering whether adjusting the movement is necessary to continuously considering the best way to proceed with the action. An advantage of the latter proposal is that it can also deal with situations in which new options become available only during the movement. And, indeed, if a better option appears during a movement, people switch to the new option with no additional delay (Brenner & Smeets 2015b, 2022a). This is an unusual situation in laboratory experiments, where the appearance of the new option is usually not completely unexpected, but in daily life one probably regularly encounters such situations, for instance, when walking in crowded environments in which options are regularly hidden from view.

Finding that people switch to a new target that suddenly appears if it is advantageous to do so supports the idea that the whole action is constantly reconsidered, because the new target was not

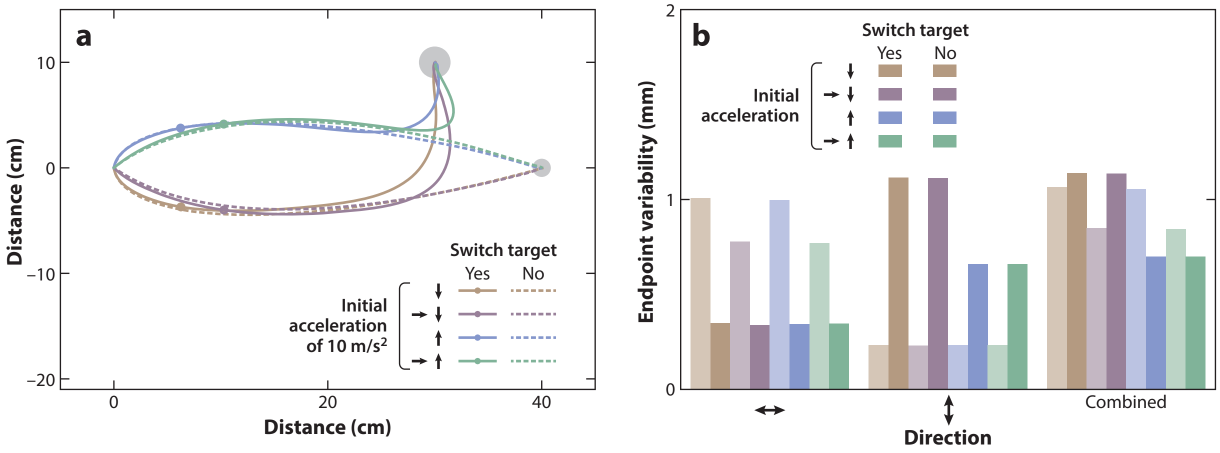

Figure 5

When is it advantageous to switch to a new target? (*a*) Trajectories in which the movement did or did not divert to a second target (*large gray disk*) that appeared after 150 ms. Simulated 500 ms movements with different initial accelerations are shown. The position of the hand when the new target appeared is indicated by the small colored disks (for the trajectories that ended at the new target). (*b*) Average endpoint variability of 10,000 simulated movements for each combination of initial accelerations. Variability was larger in the direction of the original target when moving to that target (*light bars*) and in the orthogonal direction when moving to the new target (*dark bars*).

even present at movement onset, so it is unlikely that it was considered as an option at that time. Importantly, the choice depends on the situation at the moment the new option appears (Brenner & Smeets 2022a). To illustrate this situation with our simulations, we introduced variability in the movement trajectories. This was achieved by varying the initial acceleration in two dimensions and simulating movements that do or do not switch to a new target when it appears for each of the simulated combinations of accelerations. Other than considering two dimensions (rather than only a single dimension) for each movement, the simulations were conducted in exactly the same way we conducted them for movements toward perturbed and unperturbed targets. Examples of simulated trajectories when switching to the new target, and when not doing so, for the four combinations of initial accelerations we considered are shown in **Figure 5*a***.

We simulated many trials to determine the endpoint variability. Comparing the endpoint variability when shifting or not shifting to the new target for the four combinations of initial accelerations reveals how the initial conditions might influence the choice. Variability was larger in the final movement direction: in the direction of the original target if there was no switch and in the orthogonal direction after a switch. It also depended on the initial acceleration in that direction. In terms of reducing the combined variability, it was most advantageous to switch when the movement started slowly and in the direction of the new target (blue bars in **Figure 5*b***). It was most advantageous to not switch to the new target when the movement started fast and away from the new target (purple bars in **Figure 5*b***). This corresponds well with what people do when they are actually given this choice: The average position of the hand when the new target appeared was closer to the starting point and to the new target in trials in which participants diverted their movement toward the new target, and it was further along the path and away from the new target when they kept moving toward the original target (Brenner & Smeets 2022a). The parameters in the simulation have not been matched to the actual movements, and the fact that the new target was bigger than the original one in the actual experiment is not considered, but the simulations show that the circumstances are considered in a logical manner, just as they are when avoiding obstacles in the face of perturbations or when not responding to perturbations of the original target (Nashed et al. 2012, 2014).

Briefly rotating one's hand to follow the rotation of a sphere before returning to the original, comfortable posture (Voudouris et al. 2013) and briefly following a target's displacement when one is supposed to stop moving if the target is displaced (Pisella et al. 2000) might appear to be inconsistent with constantly reconsidering one's actions. The orientation of the sphere is irrelevant as long as it remains at the same place, and there is no point in trying to reach the target precisely if reaching the target is no longer desirable. People also failed to suppress the tendency to adjust their movement in the direction in which an obstacle suddenly moved when doing so was detrimental (Aivar et al. 2008). We already discussed the fact that the time it takes to consider new visual information about the target's position depends on the kind of visual information that defines the target (Veerman et al. 2008). The delay presumably also depends on many other details. For instance, the information that is required to consider postural comfort and select new points on a rotating sphere might take longer to process and therefore be less recent when planning one's action than information about the positions of the originally planned endpoints on the sphere. Consequently, the fingers will follow the rotation of the sphere until information that reveals that moving toward different endpoints is better becomes available.

People constantly consider the latest-seen target position, but they consider target motion across an extended period of time (Brenner et al. 2023). This makes sense, because motion cannot be judged instantaneously. However, Reschechtko et al. (2023) found that people respond about 20 ms faster when an object starts to move than when a different object suddenly becomes the target. This is strange if the movements are guided by the latest information about the target's position, because the position changed more slowly when the target moved. However, it is consistent with responding faster to a single target changing position than to a target changing places with a different target (Veerman et al. 2008). In the latter case, there is a choice that is considered to be correct. When a new option appears but the participant is free to ignore it if it is not considered advantageous to switch to that target because moving to either target is considered a correct response, the latency of the response does not appear to depend on whether the previous target disappeared (Brenner & Smeets 2022a). Possibly, evaluating whether a target is a viable option takes longer when it is not immediately evident why that option would be better.

OTHER MOVEMENTS AND CONSIDERATIONS

The arguments we present are based on guiding the hand to a target in situations in which spatial precision at the endpoint is critical. The hand also appears to be guided by the latest-available information when temporal precision is critical (Brenner et al. 2014, Kreyenmeier et al. 2022). We show data for various movement times, illustrating that the benefit (or even cost) of moving slowly in terms of spatial precision depends on the circumstances. In many cases in daily life, the movement time itself is also important, independent of its effect on spatial precision. People readily learn to move accordingly (Hudson et al. 2008). Presumably the choice of (the remaining) movement time is part of the guidance process, just like the choice of a movement endpoint. To make matters even more complicated, the importance of acquiring new information about certain aspects of the environment depends on the required precision, so the information itself is likely to depend on the circumstances, because eye movements will differ in different environments (Hayhoe & Matthis 2018).

Although our arguments primarily concentrate on precision, we implicitly assume that reducing energetic costs is also important by explicitly favoring smooth movements. But energetic costs could also influence the selected endpoint, if not all endpoints have the same cost

(Moskowitz et al. 2023). We considered only two sources of variability in our simulations. The variability that we introduced by varying the acceleration by a fraction of the calculated value is reminiscent of the variability introduced by signal-dependent noise in neural control signals (Harris & Wolpert 1998). For very short movements, such as saccades, such motor variability may be the only relevant factor. But most other movements are probably guided on the basis of the latest sensory information until about 100 ms before they end. This information can be anything from the retinal position of an item that one is trying to pursue with one's eyes to the judged positions on the ground of items near to where one intends to place one's foot when walking (or the position of the foot itself). The extent to which such guidance will become evident will depend on the need to guide the movement, because constantly reconsidering the options implies that adjustments will become visible only if there is a benefit of making adjustments that exceed the (energetic) cost of doing so.

FINAL COMMENT

We presented evidence that current information is used to determine the best course of action at each moment. We consider movements that are smooth and end close to the target to be the best. We assume that the motor commands (and thereby the acceleration of the arm) that will optimize smoothness and precision (Wolpert 1997) are reconsidered at each moment on the basis of the latest-available information, leading to continuous control as in optimal feedback control (Scott 2004) or in the on-line coupling of actions to optical information (Zhao & Warren 2015). But we also assume that people reconsider the whole course of action at each moment. Constantly reconsidering endpoints when controlling movements in this manner is probably very useful for placing one's fingers at appropriate positions when reaching for objects or placing one's feet at suitable positions when walking.

SUMMARY POINTS

1. In daily life, movements must be performed in the face of considerable uncertainty. This uncertainty is dealt with by constantly guiding ongoing movements. Such guidance includes reconsidering all aspects of the movement.
2. The limiting factor in visual guidance is the delay between light reaching the eyes and the associated information influencing the movement in question.

FUTURE ISSUES

1. Other than information that takes too long to process, what are the limitations to the information that is considered?
2. Can the balance between costs and benefits be predicted rather than inferred from performance?

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LITERATURE CITED

Abekawa N, Gomi H. 2010. Spatial coincidence of intentional actions modulates an implicit visuomotor control. *J. Neurophysiol.* 103(5):2717–27

Aivar MP, Brenner E, Smeets JBJ. 2008. Avoiding moving obstacles. *Exp. Brain Res.* 190:251–64

Ansuini C, Santello M, Tubaldi F, Massaccesi S, Castiello U. 2007. Control of hand shaping in response to object shape perturbation. *Exp. Brain Res.* 180:85–96

Bennett KMB, Castiello U. 1995. Reorganization of prehension components following perturbation of object size. *Psychol. Aging* 10(2):204–14

Brenner E, de la Malla C, Smeets JBJ. 2023. Tapping on a target: dealing with uncertainty about its position and motion. *Exp. Brain Res.* 241(1):81–104

Brenner E, Driesen B, Smeets JBJ. 2014. Precise timing when hitting falling balls. *Front. Hum. Neurosci.* 8:342

Brenner E, Smeets JBJ. 1997. Fast responses of the human hand to changes in target position. *J. Mot. Behav.* 29(4):297–310

Brenner E, Smeets JBJ. 2003. Fast corrections of movements with a computer mouse. *Spat. Vis.* 16(3–4):365–76

Brenner E, Smeets JBJ. 2009. Modifying one's hand's trajectory when a moving target's orientation changes. *Exp. Brain Res.* 196:375–83

Brenner E, Smeets JBJ. 2015a. How moving backgrounds influence interception. *PLOS ONE* 10(3):e0119903

Brenner E, Smeets JBJ. 2015b. Quickly making the correct choice. *Vis. Res.* 113:198–210

Brenner E, Smeets JBJ. 2018a. Continuously updating one's predictions underlies successful interception. *J. Neurophysiol.* 120(6):3257–74

Brenner E, Smeets JBJ. 2018b. Depth perception. In *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience*, Vol. 2: *Sensation, Perception, and Attention*, ed. JT Serences, JT Wixted. Wiley

Brenner E, Smeets JBJ. 2022a. Having several options does not increase the time it takes to make a movement to an adequate end point. *Exp. Brain Res.* 240(6):1849–71

Brenner E, Smeets JBJ. 2022b. Spatial vision for action. In *Oxford Research Encyclopedia of Psychology*. Oxford University Press. **https://doi.org/10.1093/acrefore/9780190236557.013.842**

Brenner E, Smeets JBJ. 2023. Continuous use of visual information about the position of the moving hand. *Exp. Brain Res.* 241(8):2001–8

Brenner E, Smeets JBJ, de Lussanet MHE. 1998. Hitting moving targets: continuous control of the acceleration of the hand on the basis of the target's velocity. *Exp. Brain Res.* 122:467–74

Brenner E, van Dam M, Berkhout S, Smeets JBJ. 2012. Timing the moment of impact in fast human movements. *Acta Psychol.* 141(1):104–11

Bridgeman B, Stark L. 1991. Ocular proprioception and efference copy in registering visual direction. *Vis. Res.* 31(11):1903–13

Brouwer A-M, Brenner E, Smeets JBJ. 2000. Hitting moving objects: the dependency of hand velocity on the speed of the target. *Exp. Brain Res.* 133:242–48

Cámara C, de la Malla C, López-Moliner J, Brenner E. 2018. Eye movements in interception with delayed visual feedback. *Exp. Brain Res.* 236:1837–47

Camponogara I, Volcic R. 2019a. Grasping adjustments to haptic, visual, and visuo-haptic object perturbations are contingent on the sensory modality. *J. Neurophysiol.* 122(6):2614–20

Camponogara I, Volcic R. 2019b. Grasping movements toward seen and handheld objects. *Sci. Rep.* 9(1):3665

Carlton LG. 1981. Processing visual feedback information for movement control. *J. Exp. Psychol. Hum. Percept. Perform.* 7(5):1019–30

Castiello U, Bennett K, Chambers H. 1998. Reach to grasp: the response to a simultaneous perturbation of object position and size. *Exp. Brain Res.* 120:31–40

Castiello U, Bennett KMB, Stelmach GE. 1993. Reach to grasp: the natural response to perturbation of object size. *Exp. Brain Res.* 94:163–78

Česonis J, Franklin DW. 2020. Time-to-target simplifies optimal control of visuomotor feedback responses. *eNeuro* 7(2):ENEURO.0514-19.2020

Chen Z, Saunders JA. 2015. Online processing of shape information for control of grasping. *Exp. Brain Res.* 233(11):3109–24

Colby CL. 1998. Action-oriented spatial reference frames in cortex. *Neuron* 20(1):15–24

Crowe EM, Bossard M, Brenner E. 2021a. Can ongoing movements be guided by allocentric visual information when the target is visible? *J. Vis.* 21(1):6

Crowe EM, Bossard M, Karimpur H, Rushton SK, Fiehler K, Brenner E. 2021b. Further evidence that people rely on egocentric information to guide a cursor to a visible target. *Perception* 50(10):904–7

Crowe EM, Smeets JBJ, Brenner E. 2021c. The response to background motion: characteristics of a movement stabilization mechanism. *J. Vis.* 21(11):3

Crowe EM, Smeets JBJ, Brenner E. 2023. Online updating of obstacle positions when intercepting a virtual target. *Exp. Brain Res.* 241(7):1811–20

Crowe EM, Vellekoop P, van Meteren C, Smeets JBJ, Brenner E. 2022. How similar are responses to background motion and target displacements? *Exp. Brain Res.* 240(10):2667–76

Dean J, Brüwer M. 1994. Control of human arm movements in two dimensions: paths and joint control in avoiding simple linear obstacles. *Exp. Brain Res.* 97:497–514

De Comite A, Crevecoeur F, Lefèvre P. 2021. Online modification of goal-directed control in human reaching movements. *J. Neurophysiol.* 125(5):1883–98

de la Malla C, Smeets JBJ, Brenner E. 2018. Errors in interception can be predicted from errors in perception. *Cortex* 98:49–59

Desmurget M, Pélisson D, Rossetti Y, Prablanc C. 1998. From eye to hand: planning goal-directed movements. *Neurosci. Biobehav. Rev.* 22(6):761–88

Desmurget M, Prablanc C, Arzi M, Rossetti Y, Paulignan Y, Urquizar C. 1996. Integrated control of hand transport and orientation during prehension movements. *Exp. Brain Res.* 110(2):265–78

Dimitriou M, Wolpert DM, Franklin DW. 2013. The temporal evolution of feedback gains rapidly update to task demands. *J. Neurosci.* 33(26):10898–909

Elliott D, Binsted G, Heath M. 1999. The control of goal-directed limb movements: correcting errors in the trajectory. *Hum. Mov. Sci.* 18(2–3):121–36

Eloka O, Franz VH. 2011. Effects of object shape on the visual guidance of action. *Vis. Res.* 51(8):925–31

Fiehler K, Karimpur H. 2023. Spatial coding for action across spatial scales. *Nat. Rev. Psychol.* 2(2):72–84

Fitts PM, Peterson JR. 1964. Information capacity of discrete motor responses. *J. Exp. Psychol.* 67(2):103–12

Flash T, Henis E. 1991. Arm trajectory modifications during reaching towards visual targets. *J. Cogn. Neurosci.* 3(3):220–30

Fligge N, McIntyre J, van der Smagt P. 2012. Minimum jerk for human catching movements in 3D. In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE. **https://doi.org/10.1109/BioRob.2012.6290265**

Franklin DW, Reichenbach A, Franklin S, Diedrichsen J. 2016. Temporal evolution of spatial computations for visuomotor control. *J. Neurosci.* 36(8):2329–41

Gallivan JP, Chapman CS, Wolpert DM, Flanagan JR. 2018. Decision-making in sensorimotor control. *Nat. Rev. Neurosci.* 19(9):519–34

Georgopoulos AP, Kalaska JF, Massey JT. 1981. Spatial trajectories and reaction times of aimed movements: effects of practice, uncertainty, and change in target location. *J. Neurophysiol.* 46(4):725–43

Gomi H, Abekawa N, Nishida S. 2006. Spatiotemporal tuning of rapid interactions between visual-motion analysis and reaching movement. *J. Neurosci.* 26(20):5301–8

Goodale MA, Pelisson D, Prablanc C. 1986. Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature* 320(6064):748–50

Hadjipanayi V, Brenner E, Crowe EM. 2023. Slightly perturbing the arm influences choices between multiple targets. *Atten. Percept. Psychophys.* 85(6):1777–83

Harris CM, Wolpert DM. 1998. Signal-dependent noise determines motor planning. *Nature* 394(6695):780–84

Harris LR, Jenkin M, Zikovitz DC. 2000. Visual and non-visual cues in the perception of linear self motion. *Exp. Brain Res.* 135:12–21

Hayhoe MM, Matthis JS. 2018. Control of gaze in natural environments: effects of rewards and costs, uncertainty and memory in target selection. *Interface Focus* 8(4):20180009

Hesse C, Franz VH. 2009. Corrective processes in grasping after perturbations of object size. *J. Mot. Behav.* 41(3):253–73

Hoff B, Arbib MA. 1992. A model of the effects of speed, accuracy and perturbation on visually guided reaching. In *Control of Arm Movement in Space: Neurophysiological and Computational Approaches*, ed. R Caminiti, PB Johnson, Y Burnod. Springer-Verlag

Hogan N. 1984. An organizing principle for a class of voluntary movements. *J. Neurosci.* 4(11):2745–54

Hudson TE, Maloney LT, Landy MS. 2008. Optimal compensation for temporal uncertainty in movement planning. *PLOS Comput. Biol.* 4(7):e1000130

Klier EM, Angelaki DE. 2008. Spatial updating and the maintenance of visual constancy. *Neuroscience* 156(4):801–18

Knill DC, Bondada A, Chhabra M. 2011. Flexible, task-dependent use of sensory feedback to control hand movements. *J. Neurosci.* 31(4):1219–37

Kreyenmeier P, Kämmer L, Fooken J, Spering M. 2022. Humans can track but fail to predict accelerating objects. *eNeuro* 9(5):ENEURO.0185-22.2022

Kuling IA, Brenner E, Smeets JBJ. 2016. Errors in visuo-haptic and haptic-haptic location matching are stable over long periods of time. *Acta Psychol.* 166:31–36

Land MF, Hayhoe M. 2001. In what ways do eye movements contribute to everyday activities? *Vis. Res.* 41(25–26):3559–65

Liu D, Todorov E. 2007. Evidence for the flexible sensorimotor strategies predicted by optimal feedback control. *J. Neurosci.* 27(35):9354–68

MacKenzie CL, Marteniuk RG, Dugas C, Liske D, Eickmeier B. 1987. Three-dimensional movement trajectories in Fitts' task: implications for control. *Q. J. Exp. Psychol.* 39(4):629–47

Ma-Wyatt A, McKee SP. 2007. Visual information throughout a reach determines endpoint precision. *Exp. Brain Res.* 179:55–64

Medendorp WP, Goltz HC, Vilis T, Crawford JD. 2003. Gaze-centered updating of visual space in human parietal cortex. *J. Neurosci.* 23(15):6209–14

Meyer DE, Smith JE, Wright CE. 1982. Models for the speed and accuracy of aimed movements. *Psychol. Rev.* 89(5):449–82

Moskowitz JB, Fooken J, Castelhano MS, Gallivan JP, Flanagan JR. 2023. Visual search for reach targets in actionable space is influenced by movement costs imposed by obstacles. *J. Vis.* 23(6):4

Nashed JY, Crevecoeur F, Scott SH. 2012. Influence of the behavioral goal and environmental obstacles on rapid feedback responses. *J. Neurophysiol.* 108(4):999–1009

Nashed JY, Crevecoeur F, Scott SH. 2014. Rapid online selection between multiple motor plans. *J. Neurosci.* 34(5):1769–80

Oostwoud Wijdenes L, Brenner E, Smeets JBJ. 2011. Fast and fine-tuned corrections when the target of a hand movement is displaced. *Exp. Brain Res.* 214:453–62

Oostwoud Wijdenes L, Brenner E, Smeets JBJ. 2013. Comparing online adjustments to distance and direction in fast pointing movements. *J. Mot. Behav.* 45(5):395–404

Paulignan Y, Jeannerod M, MacKenzie C, Marteniuk R. 1991. Selective perturbation of visual input during prehension movements. *Exp. Brain Res.* 87:407–20

Pisella L, Gréa H, Tilikete C, Vighetto A, Desmurget M, et al. 2000. An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. *Nat. Neurosci.* 3(7):729–36

Plamondon R, Alimi AM. 1997. Speed/accuracy trade-offs in target-directed movements. *Behav. Brain Sci.* 20(2):279–303

Prablanc C, Martin O. 1992. Automatic control during hand reaching at undetected two-dimensional target displacements. *J. Neurophysiol.* 67(2):455–69

Reichenbach A, Thielscher A, Peer A, Bülthoff HH, Bresciani J-P. 2009. Seeing the hand while reaching speeds up on-line responses to a sudden change in target position. *J. Physiol.* 587(19):4605–16

Reschechtko S, Gnanaseelan C, Pruszynski JA. 2023. Reach corrections toward moving objects are faster than reach corrections toward instantaneously switching targets. *Neuroscience*. 526:135–43

Sabes PN, Jordan MI. 1997. Obstacle avoidance and a perturbation sensitivity model for motor planning. *J. Neurosci.* 17(18):7119–28

Saijo N, Murakami I, Nishida S, Gomi H. 2005. Large-field visual motion directly induces an involuntary rapid manual following response. *J. Neurosci.* 25(20):4941–51

Sarlegna F, Blouin J, Bresciani J-P, Bourdin C, Vercher J-L, Gauthier GM. 2003. Target and hand position information in the online control of goal-directed arm movements. *Exp. Brain Res.* 151(4):524–35

Sarlegna FR, Mutha PK. 2015. The influence of visual target information on the online control of movements. *Vis. Res.* 110:144–54

Saunders JA, Knill DC. 2003. Humans use continuous visual feedback from the hand to control fast reaching movements. *Exp. Brain Res.* 152:341–52

Saunders JA, Knill DC. 2004. Visual feedback control of hand movements. *J. Neurosci.* 24(13):3223–34

Saunders JA, Knill DC. 2005. Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. *Exp. Brain Res.* 162:458–73

Schmidt RA, Zelaznik H, Hawkins B, Frank JS, Quinn JT Jr. 1979. Motor-output variability: a theory for the accuracy of rapid motor acts. *Psychol. Rev.* 86(5):415–51

Scholz JP, Schöner G, Latash ML. 2000. Identifying the control structure of multijoint coordination during pistol shooting. *Exp. Brain Res.* 135:382–404

Scott SH. 2004. Optimal feedback control and the neural basis of volitional motor control. *Nat. Rev. Neurosci.* 5(7):532–45

Smeets JBJ, Brenner E. 1995. Perception and action are based on the same visual information: distinction between position and velocity. *J. Exp. Psychol. Hum. Percept. Perform.* 21(1):19–31

Smeets JBJ, Brenner E. 1999. A new view on grasping. *Mot. Control* 3(3):237–71

Smeets JBJ, Brenner E, Biegstraaten M. 2002. Independent control of the digits predicts an apparent hierarchy of visuomotor channels in grasping. *Behav. Brain Res.* 136(2):427–32

Soechting JF. 1984. Effect of target size on spatial and temporal characteristics of a pointing movement in man. *Exp. Brain Res.* 54:121–32

Stein JF, Glickstein M. 1992. Role of the cerebellum in visual guidance of movement. *Physiol. Rev.* 72(4):967–1017

Todorov E, Jordan MI. 2002. Optimal feedback control as a theory of motor coordination. *Nat. Neurosci.* 5(11):1226–35

Tresilian JR, Plooy A. 2006. Systematic changes in the duration and precision of interception in response to variation of amplitude and effector size. *Exp. Brain Res.* 171:421–35

Urbin MA. 2013. Visual regulation of overarm throwing performance. *Exp. Brain Res.* 225:535–47

van Beers RJ, Brenner E, Smeets JBJ. 2013. Random walk of motor planning in task-irrelevant dimensions. *J. Neurophysiol.* 109(4):969–77

van Mierlo CM, Louw S, Smeets JBJ, Brenner E. 2009. Slant cues are processed with different latencies for the online control of movement. *J. Vis.* 9(3):25

Van Pelt S, Medendorp WP. 2007. Gaze-centered updating of remembered visual space during active whole-body translations. *J. Neurophysiol.* 97(2):1209–20

Van Sonderen JF, Gielen CCAM, van der Gon Denier JJ. 1989. Motor programmes for goal-directed movements are continuously adjusted according to changes in target location. *Exp. Brain Res.* 78:139–46

Vaughan J, Rosenbaum DA, Meulenbroek RGJ. 2001. Planning reaching and grasping movements: the problem of obstacle avoidance. *Mot. Control* 5(2):116–35

Veerman MM, Brenner E, Smeets JBJ. 2008. The latency for correcting a movement depends on the visual attribute that defines the target. *Exp. Brain Res.* 187:219–28

Viviani P, Flash T. 1995. Minimum-jerk, two-thirds power law, and isochrony: converging approaches to movement planning. *J. Exp. Psychol. Hum. Percept. Perform.* 21(1):32–53

Voudouris D, Smeets JBJ, Brenner E. 2012. Do obstacles affect the selection of grasping points? *Hum. Mov. Sci.* 31(5):1090–102

Voudouris D, Smeets JBJ, Brenner E. 2013. Ultra-fast selection of grasping points. *J. Neurophysiol.* 110(7):1484–89

Wang H, Levi DM. 1994. Spatial integration in position acuity. *Vis. Res.* 34(21):2859–77

Warren PA, Rushton SK. 2009. Optic flow processing for the assessment of object movement during ego movement. *Curr. Biol.* 19(18):1555–60

Whitaker D, Latham K. 1997. Disentangling the role of spatial scale, separation and eccentricity in Weber's law for position. *Vis. Res.* 37(5):515–24

Wolpert DM. 1997. Computational approaches to motor control. *Trends Cogn. Sci.* 1(6):209–16

Woodworth RS. 1899. Accuracy of voluntary movement. *Psychol. Rev. Monogr. Suppl.* 3(3):i–114

Zhao H, Warren WH. 2015. On-line and model-based approaches to the visual control of action. *Vis. Res.* 110:190–202