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Review article

The multiple process model of goal-directed reaching revisited

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ABSTRACT

Recently our group forwarded a model of speed-accuracy relations in goal-directed reaching. A fundamental feature of our multiple process model was the distinction between two types of online regulation: impulse control and limb-target control. Impulse control begins during the initial stages of the movement trajectory and involves a comparison of actual limb velocity and direction to an internal representation of expectations about the limb trajectory. Limb-target control involves discrete error-reduction based on the relative positions of the limb and the target late in the movement. Our model also considers the role of eye movements, practice, energy optimization and strategic behavior in limb control. Here, we review recent work conducted to test specific aspects of our model. As well, we consider research not fully incorporated into our earlier contribution. We conclude that a slightly modified and expanded version of our model, that includes crosstalk between the two forms of online regulation, does an excellent job of explaining speed, accuracy, and energy optimization in goal-directed reaching.

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1. Introduction

Since the classic work of Woodworth (1899), a fundamental challenge in the area of perception and motor control has been to identify the sensory-motor and cognitive processes associated with rapid and accurate goal-directed upper limb movements. Woodworth held that most aiming/reaching movements were made up of two components. There was a ballistic component (i.e., an initial adjustment) designed to get the limb to the target area and then a feedback-based or homing phase to the movement (i.e., current control) that was responsible for correcting any error associated with the initial adjustment (Woodworth, 1899). This feedback-based phase was responsible for bringing the limb onto the target. The homing or corrective phase of the movement was thought to rely heavily on visual feedback about the position of the hand relative to the target. Although not stated explicitly, the planning of the ballistic phase of the movement also depends on visual information about the position of the target relative to the hand's starting point.

Over the next century, there were a number of important models of speed-accuracy relations in goal-directed aiming (e.g., Beggs and Horwarth, 1972; Carlton, 1981; Crossman and Goodeve,

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1963/1983; Elliott et al., 2001; Keele, 1968; Meyer et al., 1988; Vince, 1948). Fundamental to most of these models (cf. Schmidt et al., 1979) was the distinction between Woodworth's ballistic and feedback-based components. During the last 15 years however, many empirical studies have made it clear that the ballistic component of a typical aiming movement is not as ballistic as was previously thought (see Cluff et al., 2015 and Smeets et al., 2016 for recent reviews).

Several years ago, our group published a paper in which we presented a new model of speed-accuracy relations in goal-directed aiming (Elliott et al., 2010). Our Multiple Process Model of Goal-Directed Reaching builds on Woodworth's two-component explanation of speed-accuracy relations, but also argues for a different type of online control associated with the initial distance-covering phase of the aiming movement. This type of early control involves graded adjustments to the initial movement trajectory based on visual information about limb velocity and direction. Like Woodworth, our model includes a discrete corrective phase, late in the movement, that is based on the relative positions of the limb and the target. We have termed these two distinct corrective processes *impulse control* and *limb-target control* respectively.

Fig. 1 provides an overview of the main features of our model and the time-course of the sensory-motor processes associated with limb regulation over the trajectory of a single aiming movement. Briefly, any goal-directed aiming movement involves an initial planning (Event 1) and specification process (Event 2) that take into consideration the stochastic properties of neural-motor noise and force specification error, as well as the associated spatial error, over multiple attempts to perform the same type of movement. Aiming movements are organized to optimize not only movement speed and endpoint error, but also energy expenditure over many trials. The force-time specification process also includes the formation of an internal model of the planned movement that comprises information about both expected efference and the expected sensory consequences of the movement, including expected limb direction and velocity. Almost immediately after movement initiation, limb efference and afference regarding movement direction and velocity are compared to expectancies associated with the internal model/representation (Events 3 and 4), and graded adjustments are made to the primary acceleration and deceleration portions of the movement trajectory. This type of limb regulation can occur very rapidly (i.e., 70–85 ms; Bard et al., 1985; Zelaznik et al., 1983). Our model refers to this corrective process as *impulse control*. In parallel, afferent visual and proprioceptive information about limb position is compared to visual information about the spatial position of the target (Event 5). This information provides the basis for any late adjustment(s) to the limb trajectory that might be necessary to hit the target. We call this discrete corrective process *limb-target control* (Event 6). Limb-target regulation involves greater top-down control and therefore requires more time. Although most estimates for visual processing time in limb-target regulation are consistent with the time required for a visual reaction time (i.e., 180–200 ms; see Elliott et al., 2010 for a review), there are estimates as low as 100 ms for at least the beginning of a discrete corrective response (Paulignan et al., 1991).

As we will explain later, because it is usually strategically sound to undershoot the target with the primary movement, limb-target regulation often involves a second limb acceleration-deceleration to reach the target. At the completion of the aiming movement, terminal visual and proprioceptive feedback are processed and subsequently used to refine strategic behavior and the internal model associated with planning future movements (Event 7).

In this paper, we review the empirical and theoretical background associated with our 2010 multiple process model, and in particular impulse and limb-target control. We then evaluate and update our model based on work published both by our group and others over the last several years. Our update and evaluation includes the examination of some work published prior to 2010 that was not incorporated in our 2010 paper (Elliott et al., 2010). We also provide an expanded explanation for the role of specific types of ocular information play in limb control. Where appropriate, we acknowledge the similarities and differences between our model and other explanations of speed-accuracy relations in goal-directed aiming.

2. The multiple process model: limb-target control

Although the *iterative correction model* (Crossman and Goodeve, 1963/1983; Keele, 1968) and the *single correction model* (Beggs and Howarth, 1972; Carlton, 1981) were both timely and important variations of Woodworth's explanation of speed-accuracy relations, the most influential model of limb control has been Meyer et al.'s *optimized submovement model*. Like Woodworth, Meyer et al. (1988) held that an initial distance covering movement is planned and executed to bring the limb into the vicinity of the target. The planning of the movement however, takes into consideration stochastic principles associated with the specification and generation of the muscular forces required to move the limb (see also Schmidt et al., 1979). Specifically, multiple attempts to produce a similar aiming movement result in a normal distribution of movement endpoints centered on the middle of the target. The degree of variability associated with any set of similar movements depends on the magnitude of the muscular forces recruited to accelerate and decelerate the limb. Greater muscular forces get the limb to the target area more quickly but, on any given trial, the limb is less likely to hit the target. This outcome occurs because the distribution of primary movement endpoints is larger. A larger distribution occurs because force variability, and thus spatial variability, increase with the absolute magnitude of the forces specified to move the limb. If the limb falls outside the target area, a corrective submovement is required. Corrective submovements take time to complete. Thus, the optimal strategy is to produce movements that get the limb to the target area quickly, but not so quickly that a time-consuming corrective submovement is required on the majority of trials. As the name of the model suggests, the performer plans and executes movements that optimize movement velocity (and movement time) so that the need for corrective submovements is minimized.

Although the *optimized submovement model* provides an excellent mathematical explanation of speed-accuracy relations, including Fitts' Law (Fitts, 1954; Fitts and Peterson, 1964), the hypothesized nature of primary movements and corrective submovements is not consistent with the spatial-temporal characteristics of the trajectories seen in most three-dimensional aiming movements.[1] Specifically, the endpoint of the primary, distance-covering, phase of the movement is not centered at the middle of the target. Rather primary movement endpoints typically fall short of the target (see Elliott et al., 2004; Engelbrecht et al., 2003 and Worringham, 1991 for information about frequencies). This endpoint bias is consistent with a strategic approach to manual aiming because target overshoots are more costly in terms of both time and energy than target undershoots. Specifically, an overshoot requires the limb to cover a greater overall distance and overcome the inertia of a zero velocity situation at the point of reversal. Thus, while the performer takes into consideration the stochastic characteristics of endpoint aiming distributions (Meyer et al., 1988), these dis-

[1] Meyer et al. (1988) based their model on empirical work using wrist rotation movements that moved a cursor across a display screen. Thus, the forces required to complete the movements would be low relative to more traditional three-dimensional aiming movements (e.g., Fitts and Peterson, 1964).