

A Century Later: Woodworth's (1899) Two-Component Model of Goal-Directed Aiming

Digby Elliott
McMaster University

Werner F. Helsen
Katholieke Universiteit Leuven

Romeo Chua
University of British Columbia

In 1899, R. S. Woodworth published a seminal monograph, "The Accuracy of Voluntary Movement." As well as making a number of important empirical contributions, Woodworth presented a model of speed-accuracy relations in the control of upper limb movements. The model has come to be known as the *two-component model* because the control of speeded limb movements was hypothesized to entail both a central and a feedback-based component. Woodworth's (1899) ideas about the control of rapid aiming movements are evaluated in the context of current empirical and theoretical contributions.

More than a century ago, R. S. Woodworth (1899) published a seminal monograph reporting a number of experiments designed to elucidate the processes governing the control of goal-directed movement. Between 1972 and 2000, this monograph was cited by experimental psychologists, neurophysiologists, and movement scientists in 464 journal articles. The importance of the monograph to researchers interested in the control of goal-directed movement has been increasing almost exponentially over the past decade. Three specific issues developed in Woodworth's monograph that still appear to be relevant today are (a) determining the time required for the nervous system to process and use visual response-produced feedback, (b) identifying the variables responsible for the relation between the speed and accuracy of goal-directed arm movements, and (c) uncovering the movement control processes that are responsible for manual asymmetries in the performance of goal-directed movements.¹

In studying these and other motor control and learning issues, Woodworth (1899) developed a model of limb control that still provides a viable framework for how simple target-aiming movements are controlled. In this review, we follow Woodworth's

two-component model of limb control into the 21st century. After describing Woodworth's original work, we first examine how his model and other models of limb control have developed over the years, and we evaluate how well they account for both performance and kinematic evidence gathered in the study of speed-accuracy relations in goal-directed aiming. We then examine the two-component model and other models of limb control in the context of a number of perturbation studies and recent evidence about the changing nature of limb control with practice. As well, we review how the recent literature on eye-hand coordination contributes to our understanding of upper limb control. Finally, we summarize the contribution of Woodworth's 1899 monograph in the context of the most recent empirical and theoretical developments, and we highlight a number of issues that are yet to be resolved.

Historical Review: The Two-Component Model and Visual Processing Time

Woodworth's (1899) experiments involved an aiming procedure in which participants made horizontal sliding movements with a pencil on paper secured to a drum rotating at a constant speed. The movements were made back and forth (i.e., reciprocally) over the surface of the paper. Participants either performed their movements between lines a fixed distance apart or matched the amplitude of a particular movement to the previous attempt. Thus, Woodworth was able to measure not only the spatial accuracy and consistency of the movement endpoints but also the spatiotemporal characteristics of the trajectory. For most aiming attempts, the initial portion of the movement was relatively rapid and stereotyped. However, as the pencil approached the target (or target distance), the movement became slower and was characterized by

Digby Elliott, Department of Kinesiology, McMaster University, Hamilton, Ontario, Canada; Werner F. Helsen, Department of Kinesiology, Katholieke Universiteit Leuven, Leuven, Belgium; Romeo Chua, School of Human Kinetics, University of British Columbia, Vancouver, British Columbia, Canada.

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Correspondence concerning this article should be addressed to Digby Elliott, Department of Kinesiology, McMaster University, Hamilton, Ontario L8S 4K1, Canada. Electronic mail may be sent to elliott@mcmaster.ca.

¹ We do not deal with the issue of manual asymmetries in this article. For a current review, see Elliott and Chua (1996).

discontinuities in the time-displacement profile. As well, there was more trial-to-trial variability for this part of the trajectory.

Woodworth (1899) suggested that aiming movements are composed of an initial impulse phase and a current control phase. The initial impulse was hypothesized to be under central control and designed to bring the limb into the vicinity of the target. Once in the region of the target, the limb comes under current or feedback-based control. In this second "homing" phase, visual information about the relative positions of the limb and target is used to make any adjustments to the movement trajectory necessary to bring the limb to rest on the target. These adjustments can take the form of "little extra movements" (p. 54) added after the initial impulse or "a subtraction or inhibition of the movement, making it shorter than it would otherwise have been" (p. 58). The former type of current control appears to refer to discrete corrections investigators now identify with discontinuities in the movement trajectory (e.g., Meyer, Abrams, Kornblum, Wright, & Smith, 1988). Subtraction or inhibition, on the other hand, could imply either discrete antagonist activity during deceleration or graded modulation of the muscular forces used to propel and/or brake the movement (e.g., Elliott, Carson, Goodman, & Chua, 1991).

To examine the relation between speed and accuracy, and the contribution of vision to current control, Woodworth (1899) had participants perform their aiming movements to the beat of a metronome set at a number of different speeds. In one situation, participants made their aiming movements with their eyes open, whereas in a second condition they were asked to close their eyes. As the metronome speed increased (i.e., as the individual movement times decreased), the error in the eyes-open condition approached the error in the eyes-closed condition. The idea was that the temporal constraints of the movement limited the opportunity for current control. At movement times of approximately 450 ms, there was no difference between errors in the eyes-open and eyes-closed condition, presumably because the movement now involved only an initial impulse and no current control phase.

Until the late 1960s, Woodworth's (1899) most significant finding was considered his determination of the time to use visual feedback. Interestingly, it was this empirical contribution that appears to have been the most in error. Because Woodworth used reciprocal movements in his experiments, the duration of individual aiming attempts included not only the time the limb spent sliding across the paper but also the time required to reverse the direction of the movement after a previous target position had been achieved (see also Vince, 1948).

In 1968, Keele and Posner published an influential study that reduced Woodworth's (1899) estimate of visual processing time substantially. Rather than examining reciprocal movements, Keele and Posner (1968) had participants perform discrete aiming movements in a situation in which the ambient lighting in the room could be extinguished on movement initiation. For a series of trials, participants would perform at a target movement time, and on half the trials the room lights were extinguished on movement initiation. When participants were moving more slowly (e.g., for movement time conditions of 260 ms, 350 ms, and 450 ms), they performed more accurately in conditions in which vision was available during aiming. However, for the 190-ms movement time condition, there was no difference between the lights-on and the lights-off condition. This led Keele and Posner to conclude that the

time required for the visual feedback loop to operate was somewhere between 190 and 260 ms.

In Keele and Posner's (1968) study, the trial-to-trial availability of vision was manipulated randomly ($p = .5$). Zelaznik, Hawkins, and Kisselburgh (1983) reasoned that if participants were uncertain about the availability of vision on a particular trial, they may have prepared their movements differently, especially when they were required to move to the target quickly. By blocking rather than randomizing the availability of visual feedback during manual aiming, Zelaznik et al. were able to demonstrate an accuracy difference between vision and no-vision conditions for movement times as short as 100 ms (see also Elliott & Allard, 1985). Of course, it is possible that under blocked feedback conditions, visual information during an aiming movement benefits subsequent movements rather than the movement in progress. Thus, accuracy differences between lights-on and lights-off conditions for rapid movements could reflect "feedforward" advantages related to the preparation and execution of the next movement rather than rapid on-line processing of the feedback. In this context, Ghez, Gordon, Ghilardi, and Sainburg (1995) recently showed that patients with impaired proprioception were able to use visual feedback from a preceding trial to reduce target-aiming error on a subsequent no-vision trial. Henderson (1977) also reported a between-trials impact of visual monitoring for dart-throwing.

To explore a feedforward interpretation of their trial blocking results, Zelaznik et al. (1983) conducted a follow-up experiment in which they alternated vision and no-vision trials, creating a situation in which participants always knew in advance about the availability of vision, but one in which any feedforward benefits from a vision trial (e.g., trial N) would have their greatest impact on the preparation of a subsequent no-vision aiming attempt (e.g., trial $N + 1$). Although the movement times used in this experiment were longer than those used previously, Zelaznik et al. demonstrated that use of on-line visual feedback (e.g., the information available during a particular trial) was more important than the trial context (e.g., information available on the previous trial that contributes to feedforward control).

In summary, Zelaznik et al.'s (1983) work, along with research reviewed later in the article, indicates that on-line vision provides accuracy advantages, even for very rapid movements (see Carlton, 1992). This finding has implications for any model of speed-accuracy relations in goal-directed movements, and especially Woodworth's (1899) two-component model, which holds that movement accuracy depends on the time available for current control.

Other Models of Speed-Accuracy Relations in Goal-Directed Movement

The Iterative Correction Model

Although important empirical work on visual and kinesthetic feedback loops (e.g., Annett, Golby, & Kay, 1958; Vince, 1948) and speed-accuracy relations (e.g., Fitts, 1954; Fitts & Peterson, 1964) was conducted in the mid-20th century, the first processing-based model to build on Woodworth's (1899) two-component

model of limb control did not appear until the 1960s.² The iterative correction model was first proposed by Crossman and Goodeve (1983) at a meeting of the Experimental Psychology Society in England. Several years later, it was refined by Keele (1968). The model was designed to explain the relation between speed and accuracy in reciprocal (Fitts, 1954) and discrete (Fitts & Peterson, 1964) aiming that has come to be known as Fitts' law. Rather than depending on a single ballistic and feedback phase for limb control, the iterative correction model held that movements were composed of consecutive ballistic phases that were prepared based on the visual and other feedback obtained during the previous phase. Each submovement was assumed to be of a similar duration, and the error associated with a submovement was proportional to the remaining distance to the target (Keele, 1968). Thus, following the initial movement toward the target, subsequent submovements were essentially corrections with less inherent error because they covered smaller distances. Final endpoint accuracy was dependent on the number of corrective movements. The limiting factor in the corrective process and therefore accuracy was the time required for visual feedback loops to operate and thus the number of corrective submovements possible for a given movement time. In the 1960s, this "visual correction time" was estimated to be approximately 200 ms (Keele & Posner, 1968). In terms of speed-accuracy then, movement time, and hence Fitts' law, was dependent on the number of submovements required to reach the target.

Although the Crossman and Goodeve (1983)-Keele (1968) model of limb control did an excellent job of mathematically accounting for the relation between speed and accuracy (Fitts, 1954; Fitts & Peterson, 1964), the notion that there are discrete changes in the limb's trajectory every 200 ms, or at any fixed temporal interval, was inconsistent with kinematic evidence obtained from high-speed film (e.g., Langolf, Chaffin, & Foulke, 1976) and optoelectric technology that now make it easy to reconstruct limb trajectories in three-dimensional space (for a review, see Elliott, Binsted, & Heath, 1999). On the basis of these sorts of data, Keele (1981) abandoned the iterative correction model of limb control in favor of a single-correction model of speed-accuracy relations.

The Single-Correction Model

The single-correction model of speed-accuracy relations was put forth by Beggs and Howarth (1970, 1972; Howarth, Beggs, & Bowden, 1971) in the early 1970s. In some respects, the model resembled Woodworth's (1899) two-component description of limb control. Specifically, an initial ballistic movement was thought to bring the limb into the proximity of the target area, after which a single correction occurred based on visual feedback. On the basis of the notion that there is a minimal time interval required for a correction to be realized, the single correction was thought to occur at a fixed interval before target acquisition. The precision of the single correction and therefore the accuracy of the movement were dependent on the proximity of the limb to the target when the corrective movement was initiated. For longer duration movements, the limb was thought to be closer to the target when the correction took place, thus explaining the relation between movement speed and accuracy. The two-component model and the single-correction model are often taken as the same explanation of

limb control. However, a distinction should be made between a single programmed correction and the type of visual homing associated with the second phase of the movement as proposed by Woodworth.

The two-component and the single-correction model of limb control share a number of features that make them difficult to distinguish empirically based solely on performance data. For example, both models are grounded on the premise that error is reduced via the detection and correction of error in the movement trajectory. Because visual information is the most reliable information about the position of the limb in three-dimensional space and is usually the only information about the position of the target, both models predict that elimination of one or both sources of information following movement initiation should lead to increased target-aiming error. According to the two-component model, the elimination of visual information late in the trajectory (i.e., during the homing phase of the movement) should lead to the greatest increases in error. For the single-correction model, the predictions are less clear. If there is some fixed period of time just before target acquisition, after which visual feedback processes no longer have time to operate, then visual information about the target and/or limb position during that period should have no impact on performance. Presumably, the interval just before the correction should be most important for the pickup of visual information.

In an attempt to determine the duration of the period before target acquisition during which vision is no longer useful, Beggs and Howarth (1972) used a procedure in which participants made aiming movements of different speeds and distances while the experimenters eliminated vision when the limb was a fixed distance (and a known time) from acquiring the target position. In line with the single-correction model, they found that occluding vision of the hand and target approximately 290 ms prior to the termination of the movement had little or no impact on performance. This estimate of visual processing time was reasonably consistent with Keele and Posner's (1968) findings, and through the 1970s it was generally assumed that movements of less than 250 ms were controlled centrally, because there was no time for visual feedback loops to operate (e.g., Schmidt, 1976).³

On the basis of the notion that some portion of the movement must occur before any error in the movement trajectory can be detected and that some period of time is necessary to complete the

² Researchers interested in speed-accuracy relations have adopted one of two approaches. They have either manipulated movement time, through the use of a metronome or training, and measured movement errors (e.g., Woodworth, 1899), or they have constrained movement accuracy by creating specific target boundaries and measured the movement time required to achieve that degree of accuracy (e.g., Fitts & Peterson, 1964). In the former case, there appears to be a linear relation between movement time and endpoint variability (e.g., Meyer, Smith, & Wright, 1982). In the latter case, there is a log relation between the accuracy demands and movement time. This relation is best characterized by Fitts' law (Fitts, 1954). The difference between the form of the relation in time-constrained and accuracy-constrained situations may be due to the added cognitive requirement of maintaining a fixed movement time in the first circumstance (Carlton, 1994).

³ As Carlton (1992) pointed out, there is some evidence in Beggs and Howarth's (1972) own data that participants benefited from vision for movement times as short as 165 ms.

corrective process, Carlton (1981a) argued that the 200–300 ms estimates of visual processing time were conservative. He used an aiming protocol in which a barrier blocked vision of the limb for the initial portions of the movement trajectory. Using this procedure, he found that only vision of the last 25% of the movement trajectory was important for movement accuracy. In terms of time, this was approximately 135 ms. Carlton's (1981a) finding that only visual information from the last 25% of the movement was useful for limb control is consistent with the two-component model of limb control.⁴ Although Chua and Elliott (1993) also reported that the final portion of the movement trajectory is important for aiming accuracy, there is some evidence that very early visual information may play a role in limb control.

Bard, Hay, and Fleury (1985) had participants aim at targets in space by making rapid punching movements of their hand. As well as examining movement time, they independently manipulated vision of the first half and the second half of the movement trajectory. Unlike some of the previous studies, in this study the researchers were interested only in directional (i.e., right–left) accuracy, as opposed to amplitude accuracy or both amplitude and directional accuracy. For movement times of less than 110 ms, Bard et al. found that vision during either the initial or final portion of the trajectory was better than a completely open-loop situation. However, this situation was not as good as when full visual information was available. Interestingly, for slow movements (290 ms), only vision of the final portion of the trajectory was helpful. Thus, it would appear that at least for directional accuracy, early visual information is necessary (see Elliott & Allard, 1985). Because Bard et al. did not examine the actual path of the movement, it was not known when adjustments based on this early visual information were made.

Both the two-component model of limb control and the single-correction model of limb control hold that the corrective process is based on information about the relative positions of the limb and the target. A number of experimenters have attempted to examine this aspect of the model by independently manipulating information available from these two sources. For example, Carlton (1981b) had participants make 300-to-360-ms aiming movements in five different visual circumstances. The extreme conditions involved full vision and a situation in which the room lights were extinguished on movement initiation. He also used phosphorescent tape to provide participants with visual information about the target only, the limb only, or both the target and the limb in an otherwise dark aiming environment. Interestingly, he found that participants performed with equivalent accuracy in the full vision, the limb only, and the limb and target conditions. Performance in the target-only condition was no better than the no-vision situation. In studies designed to examine manual asymmetries in aiming, Carson and colleagues (Carson, Chua, Elliott, & Goodman, 1990; Carson, Goodman, Chua, & Elliott, 1993) replicated Carlton's (1981b) work a number of years later. These findings were contrary to predictions by Stubbs (1976), who reasoned that target information should be most important for feedback-based control, because even in the dark, participants have kinesthetic and efferent information available about the position of their limb.

Carlton (1981b) suggested that his failure to find any accuracy benefit attributable to target information could be because target information persists over the brief period required to complete the aiming movement. Elliott (1988) tested this hypothesis directly by

having participants aim to small targets with full vision, no vision, or vision of the stylus only. In the latter two situations, the room lights were extinguished either on movement initiation or 2 and 10 s before the movement began. Regardless of whether the stylus was visible or not, the 2- and 10-s no-vision periods contributed to a large increase in target-aiming error compared with the lights-off-on-movement initiation condition. This result occurred regardless of whether participants were making rapid (200–300 ms) or slow (400–500 ms) movements. Presumably, the 2- and 10-s periods without vision were sufficient for information about the target's position to deteriorate (see also Elliott & Madalena, 1987). This was confirmed in a second experiment in which the impact of the no-vision delay was eliminated simply by using a phosphorescent target (Elliott, 1988). The finding that both limb and target information is important for aiming is consistent with both the single-correction and the two-component model of limb control.

The Impulse Variability Model

In the wake of rather long estimates of visual processing time (Beggs & Howarth, 1972; Keele & Posner, 1968; Vince, 1948; Woodworth, 1899), Schmidt and colleagues (Schmidt, Zelaznik, & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979) introduced a model of speed–accuracy relations in goal-directed movement that did not include a feedback-based corrective process. The model was based on the premise that variability in the muscular forces used to propel the limb toward the target increased proportionally with the absolute forces required for a particular movement type. Greater force and thus greater force variability are associated with faster movements and movements that cover greater distances. Increased trial-to-trial variability in force production leads to greater spatial variability in terms of movement endpoint. This translates into increased variable error or effective target width relative to that which would be associated with a less forceful movement situation. Schmidt and colleagues (1978, 1979) have shown that both an increase in movement amplitude and a decrease in movement time lead to a linear increase in effective target width, but only for movements that require less than 200 ms to complete. Presumably, for longer duration movements, there is the opportunity for feedback-based corrective processes to operate. Although in terms of Woodworth's (1899) two-component model, the force–force variability relation pertains only to the initial impulse phase of the movement, variability in the initial impulse determines the degree to which feedback-based corrective processes are necessary. It is also the main determinant of endpoint consistency when feedback is not available (Wallace & Newell, 1983). This feature of the force–force variability relation provided the basis for the development of Meyer and colleagues' (1988) dual-process model of limb control.

Optimized Submovement Model

For the last decade, the optimized submovement model has been the most influential explanation of speed–accuracy relations in goal-directed aiming movements (Meyer et al., 1988). Developed

⁴ In fact, Carlton (1981a) found that even visual information of the last 7% of the movement was useful for improving the precision of the aiming.

to account for speed–accuracy relations in spatially constrained tasks (i.e., tasks in which participants are required to terminate their movements within a target area while minimizing movement time), the model proposes that rapid aiming movements are made up of component submovements whose durations are optimized in order to cope with a noisy neuromotor system. The optimized submovement model evolved from a synthesis of features of the impulse variability model and the iterative correction model, and it thus not only captures the inherent variability associated with movement production but also recognizes the importance of corrective processes late in the movement.

The model holds that movement production is characterized by an optimal compromise between (a) the greater neuromotor noise and potential endpoint variability associated with a more forceful movement and (b) the time-consuming requirements of corrective submovements. Initial impulse and optional corrective submovements are combined in order to minimize overall movement time while still meeting the accuracy requirements imposed by the target. Over a series of aiming attempts at the same target, a normal distribution of primary submovement endpoints around the center of the intended target is expected because of stochastic noise in the motor system. When the primary movement endpoint falls outside the target boundary, a corrective submovement is necessary. The endpoints of these submovements over a series of trials are again normally distributed around the center of the target. This means that a correction to the correction may be required on a small proportion of trials (Meyer, Smith, Kornblum, Abrams, & Wright, 1990). This latter feature of the model makes it clearly different from the single-correction model.

The corrective submovements in the optimized submovement model are based on visual and other feedback about the predicted endpoint of the primary submovement, and on some occasions, subsequent submovements. Nevertheless, like the iterative correction model and the single-correction model, the corrective process is discrete and intermittent. That is, once a submovement is under way, it continues unchanged by feedback until it is completed. Thus, the visual information available prior to the initiation of any submovement is extremely important.

The optimized submovement model is able to account for speed–accuracy relations for movements of short and long duration because of the integration of both impulse variability and feedback-based corrective processes. Thus, the model combines the best features of the impulse variability model and the iterative correction model. The main strength of the model is its mathematical sophistication (cf. Woodworth, 1899) in explaining the well-known speed–accuracy relation in goal-directed aiming (Fitts, 1954; Fitts & Peterson, 1964). On the basis of assumptions regarding stochastic noise in the motor system and its effects on submovement endpoint distribution, production of component submovements, and the optimization of submovement and total movement durations, the optimized submovement model makes a number of quantitative, and testable, predictions about the characteristics of rapid, spatially constrained aiming movements. These mathematical predictions concern the key variables of mean total movement time, mean durations of component submovements, submovement endpoint variability, and the relative frequency of submovements and errors, as a function of the target distance and width (see Meyer et al., 1988, for details on mathematical relations). Meyer et al. (1988) showed that mean total movement and

submovement durations conform to a square-root approximation of Fitts' law. They also confirmed the positive relation between spatial endpoint variability and movement velocity.

The original optimized submovement model (Meyer et al., 1988) has itself undergone modification, specifically to allow for the presence of multiple corrective submovements (Meyer et al., 1990; cf. Meyer et al., 1988). Meyer et al. (1990) outlined how different forms of speed–accuracy relations (i.e., linear, square-root, logarithmic) can be derived hypothetically from an optimized multiple submovement model. This potential capacity to account for different speed–accuracy relations adds some appealing generalizability to the model.

Although the models proposed by Meyer and colleagues (1988, 1990) present a more sophisticated dual-process explanation of speed–accuracy relations than Woodworth (1899) was able to provide, there remain a number of theoretical and empirical issues with the predictions of the model as Meyer et al. (1988) themselves admitted. We turn next to recent kinematic evidence on limb control that is relevant to the optimized submovement model and other dual-process models of speed–accuracy relations in goal-directed movement.

Dual-Process Models of Limb Control: The Kinematic Evidence

Although it is difficult to distinguish among the predictions of the single-correction, the two-component, and the optimized submovement model of limb control based on performance data, information regarding the actual movement trajectories provides some insight. The first investigations to incorporate a detailed kinematic analysis were concerned with the impact of accuracy demands on the movement trajectories. A number of investigators demonstrated that decreasing the size of the target results in changes to the shape of the velocity profile (Langolf et al., 1976; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Soechting, 1984). That is, although the profiles were relatively symmetric for large targets, participants spent more actual time, and therefore a greater proportional time, after peak velocity when aiming at small targets. Presumably, this additional time is necessary to process and use the visual and kinesthetic feedback to modulate deceleration and/or to make the discrete corrections required to bring the limb to rest on the smaller target. This extra time after peak velocity is consistent with Woodworth's (1899) two-component model of limb control. However, it is only consistent with the single-correction model of limb control if the single correction associated with smaller targets takes more time or occurs later in the primary deceleration phase of the movement. The dependence of the degree of symmetry of the velocity profile on the difficulty and accuracy requirements of the movement is in contrast with assumptions of the optimized submovement model, which posits that the velocity profiles of both the primary submovement and any corrective submovements should be symmetric.

Carlton (1979) examined the viability of intermittent models of limb control (i.e., the iterative correction model and the single-correction model) by looking for the presence of discontinuities in the movement pattern. Using high-speed film, he monitored participants performing two aiming movements of intermediate dif-

ficuity (e.g., 4.58 and 5.58 bits).⁵ He found that most movements were composed of at least two submovements: "The first or initial movement ended somewhat short of and above the target, and was followed by a final corrective movement which brought the stylus into contact with the target" (Carlton, 1979, p. 122). Carlton's (1979) data were consistent with a single (discrete) correction model of limb control, but not the very conservative estimate of the visual sampling lag proposed by Beggs and Howarth (1970), because discrete "corrections" were evident in the movement trajectory for movements much shorter than 290 ms. Following Annett et al. (1958), Carlton (1979) assumed that the type of visual homing associated with the two-component model would be characterized by a slow constant velocity movement phase just prior to contact with the target. This was not the case, and in fact there was often an increase in velocity just prior to target acquisition. On these trials, it was contact with the target surface that abruptly terminated the movement. Presumably, this strategy allows the performer to maximize movement speed during the final approach to the target while minimizing the energy requirements for braking the movement.

Carlton's (1979) finding that the primary movement generally undershoots the target is not consistent with one of the primary assumptions of the optimized submovement model. Specifically, Meyer et al. (1988) held that errors in both the initial and subsequent submovements are normally distributed around the center of the target. For three-dimensional aiming movements (e.g., Carlton, 1979), and two-dimensional aiming involving the movement of a mouse on a graphics tablet (e.g., Chua & Elliott, 1993), this is seldom the case. Like Carlton (1979), we have demonstrated that for movements at the midline, away from the body, participants almost always undershoot the target with their initial submovement (Chua & Elliott, 1993; Elliott, Chua, Pollock, & Lyons, 1995; Elliott, Heath, et al., 1999; Elliott, Lyons, & Dyson, 1997; see also Worringham, 1991). This strategy to undershoot the target with the initial impulse makes sense because it is more economical, in terms of both time and energy, to correct a movement that falls short of the target than to correct an overshoot (see Barrett & Glencross, 1989; Guiard, 1993; Sparrow & Newell, 1998). In the case of an overshoot, the limb moves a greater distance overall before it finally comes to rest on the target. This added distance is associated with extra time and mechanical energy, partly because the limb must overcome the inertia of a zero-velocity situation at the point of reversal. For a movement extension, there is already a positive velocity in the direction of the target when additional muscular force is applied. From a processing point of view, the reversal in direction required by a target overshoot entails a change in the role of the muscles driving the movement; that is, the agonist muscles for the initial impulse become the antagonist muscles for the reversal and vice versa. In this context, reversal movements have been shown to be more attention demanding than extensions to an ongoing movement made in the same direction (Brebner, 1968).⁶

Following Carlton (1979), Jagacinski, Repperger, Moran, Ward, and Glass (1980) made another early attempt to describe the trajectories of simple goal-directed movements. They used a computer aiming task in which participants manipulated a joystick to move a cursor to a target on an oscilloscope screen and conducted a detailed analysis of submovement structure. Contrary to the iterative correction model, Jagacinski et al. found that the first

movement occupied a much longer duration than subsequent "corrective" movements. Although their task involved long movement times (i.e., 500 to 1,600 ms), many of the movements exhibited multiple discontinuities during the approach to the target (i.e., more than a single correction). Whether or not what Jagacinski et al. reported can be considered feedback-based homing (e.g., Woodworth, 1899) depends on semantics.

With the advent of high-speed optoelectric technology and the development of more sophisticated computer aiming tasks in the 1980s (see Elliott & Carson, 2000), there have been many studies designed to examine the spatiotemporal structure of movement trajectories in goal-directed aiming. For our purposes, the experiments in which visual information about the movement of the limb and/or the target position was manipulated are of greatest interest.

The development of the optimized submovement model was based on data acquired using a one-dimensional computer aiming task in which participants produced wrist rotation movements in order to move a cursor toward targets on a CRT screen (Meyer et al., 1988). Using a movement parsing procedure similar to Jagacinski et al.'s (1980), Meyer and colleagues partitioned their aiming movements into primary and secondary (corrective) components. Consistent with their hypothesis about the relation between the accuracy requirements of a movement and the optimization of movement time, Meyer et al. (1988) found that the endpoint variability of the primary movement increased linearly with the average velocity of the movement. This was the case when vision of the cursor was available over the complete course of the aiming movement and when it was eliminated on movement initiation. Although there were no differences in endpoint variability for the primary movement when the cursor was visible and invisible, the endpoint variability of secondary submovements was greater in the invisible cursor situation. Because participants exhibited just as many corrective submovements in the no-cursor condition, Meyer

⁵ These numbers refer to the index of difficulty as defined by the Fitts' (1954) equation: Index of difficulty = $\log_2(2 \times \text{movement amplitude} / \text{target width})$. When index of difficulty is manipulated (i.e., when the accuracy requirements of the movement are varied), movement time becomes the primary dependent variable. For both reciprocal (Fitts, 1954) and discrete aiming movements (Fitts & Peterson, 1964), there is a linear relation between index of difficulty and movement time.

⁶ There are some situations in which the initial movement is actually more likely to overshoot than undershoot the target. This usually involves single-dimension movements in which one large muscle group is used to propel the limb (agonist) and another large muscle group brakes the limb (Khan & Franks, 2000). The primary movement endpoint bias occurs when the limb reaches relatively high velocities and the elastic properties of the antagonist muscle group are used to pull the limb back to its final resting position. In this situation, it is not the use of feedback but the mechanical properties of the effector that are responsible for the reversal. In the examination of elbow flexion, Khan and Franks (2000) concluded that an efficient strategy was "to produce fast movements which overshoot the target and then spring back toward the target [rather] than to reduce movement speed to the extent that oscillations are eliminated. Because the oscillations are caused by passive mechanical factors, they do not involve costs associated with active control processes such as programming changes in the sequencing of agonist-antagonist activation patterns. Furthermore, maintaining high velocities, but travelling a longer distance by overshooting the target, may outweigh the benefits of reducing oscillations by slowing down the velocity of the initial impulse" (p. 237).

et al. (1988) concluded that the corrective process was based on less precise kinesthetic information when vision was not available. These data once again confirm the importance of visual feedback during goal-directed aiming movements.

Using a more traditional three-dimensional aiming paradigm, Elliott et al. (1991) had participants move to small targets in a condition involving full visual information and in a situation in which the room lights were extinguished on movement initiation. The latter procedure eliminated information about both the limb and the target. On some blocks of trials movement accuracy was stressed, whereas on other blocks participants were asked to move as rapidly as possible. Although the impact of vision was most pronounced when participants were attempting to be accurate, in both instructional situations the availability of vision had a clear impact on the characteristics of the movement trajectories. Specifically, participants spent more real and proportional time after peak velocity when vision was present throughout the course of the movement. Because the visual manipulation did not affect early kinematic markers like peak velocity or time to peak velocity, Elliott et al. (1991) concluded that the extra time after peak velocity was used to process visual feedback in order to reduce target-aiming error. In fact, variable target-aiming errors were reduced by 40% in the speed condition and 300% in the accuracy condition when visual information was available. Although many of the acceleration profiles had discrete discontinuities following peak velocity, there were no more "corrections" in the vision conditions than in the no-vision situations. This led Elliott et al. (1991) to suggest that visual control may proceed in a more continuous manner with graded adjustments to the muscles being used to decelerate the movement.⁷

The impact of vision on the symmetry of the movement trajectory has been reported a number of other times, both with three-dimensional aiming movements (e.g., Carson et al., 1993) and with computer aiming tasks (Chua & Elliott, 1993; Elliott et al., 1997). In situations requiring greater accuracy, there are typically multiple discontinuities in the movement trajectory during the primary deceleration phase of the movement (Carson et al., 1993; Chua & Elliott, 1993).⁸ Although in some studies discontinuities are more prevalent in the presence of vision (Chua & Elliott, 1993; Khan & Franks, 2000), this is not always the case (Elliott, Binsted, & Heath, 1999; Elliott et al., 1991; Meyer et al., 1988). To date, we have been unable to identify any single variable responsible for these between-experiments differences in the presence of discontinuities. It is clear, however, that when vision is available, less error occurs when participants spend more time in the deceleration phase of their movements (Chua & Elliott, 1993). This finding once again supports the notion of some form of continuous control (e.g., Woodworth, 1899; cf. Beggs & Howarth, 1970, 1972; Crossman & Goodeve, 1983; Meyer et al., 1988).

The kinematic aiming studies involving the manipulation of vision have consistently shown that participants spend a greater proportion of their overall movement times after peak velocity when vision is available than when it is occluded on movement initiation. Because target-aiming error is always greater in no-vision situations, this extra time seems to be used for the feedback-based reduction of aiming error. Interestingly however, this extra time after peak velocity cannot always be attributed to discrete corrections in the movement trajectory. Although there are certainly shortcomings associated with any set of rules used to iden-

tify discontinuities in velocity and/or acceleration (Chua & Elliott, 1993; Jagacinski et al., 1980; Meyer et al., 1988; van Donkelaar & Franks, 1991; Walker, Philbin, Worden, & Smelcer, 1997), it may also be the case that aiming movements are regulated by vision in a continuous manner.

We (Elliott, Binsted, & Heath, 1999) recently attempted to isolate this type of control using within-subject correlation procedures. Participants performed 40-cm, left-to-right aiming movements across the midline to small targets. In one condition, they had full visual information available to them throughout their aiming attempt, whereas in a second condition liquid crystal goggles were used to eliminate vision on movement initiation. Movement trajectories for each trial were then segmented, and the distances covered between movement initiation and peak velocity, and between peak velocity and the end of the movement, were calculated. Elliott, Binsted, and Heath (1999) reasoned that for precise target aiming, early amplitude error-variability must be compensated for during the deceleration portion of the movement, and that this compensation, or error reduction, process would be more efficient when visual information is available than in its absence. To examine this hypothesis, they calculated within-subject correlation coefficients between the distance covered between the beginning of the movement and peak velocity, and between peak velocity and the end of the movement (see Elliott, Binsted, & Heath, 1999). Although the correlation coefficients were reliably different from zero and negative in both the vision and no-vision situations, they were significantly more robust when vision was available. There was also less target-aiming error in the vision condition than the no-vision condition, but no more discrete discontinuities in the movement trajectories. Thus, it appears that although discrete adjustments to the trajectory occur on most aiming attempts that require spatial precision, there is also a more continuous form of visual control over the deceleration phase of the movement.

Another way we have attempted to quantify continuous control has been to examine changes in the spatial variability of the movement as the movement progresses. In a recent study, we had participants make rapid aiming movements to targets of three different sizes both in a full-vision situation and when liquid crystal goggles were used to occlude vision of the limb and target on movement initiation (Khan, Coull, Chua, Lyons, & Elliott, 2000). In a first experiment, participants completed their aiming movements under conditions in which vision condition was either blocked or randomized. In a second experiment, vision and no-vision trials were alternated. These order-prior knowledge manipulations were introduced in order to distinguish the within-trial, on-line influence of vision from any between-trials feedforward

⁷ Elliott et al. (1991) pointed out that what appears to be continuous control could reflect "many overlapping discrete adjustments to the movement trajectory giving the movement the appearance of continuity (i.e., pseudo-continuous)" (p. 415).

⁸ On a small number of aiming trials, discontinuities in acceleration are sometimes found before peak velocity (see Chua & Elliott, 1993). Because these sometimes occur within 80 to 100 ms of movement initiation (i.e., no time for feedback to operate), they are usually considered to be corrections based on feedforward or efference (see Beaubaton & Hay, 1986).

contribution (see Keele & Posner, 1968, vs. Ghez et al., 1995; Henderson, 1977; Zelaznik et al., 1983).

Over all the trials in any given condition, we calculated a standard deviation for the spatial position of the aiming stylus in both the primary direction of, and perpendicular to, the direction of movement at peak acceleration, peak velocity, peak deceleration, and the end of movement. Interestingly, when participants knew that vision would be available to guide their aiming (i.e., blocked and alternating conditions), they spent significantly less time preparing the movement (i.e., reaction time) than they did under either no-vision conditions or conditions of feedback uncertainty. Of greater interest were the variability findings. Specifically, whereas variability was independent of vision condition at peak acceleration and peak velocity, participants actually exhibited greater amplitude variability at peak deceleration when vision was available than when it was absent, regardless of whether vision was blocked or randomized. Although there was a large decrease in variability between peak deceleration and the end of the movement for both vision and no-vision trials, amplitude endpoints were reliably more consistent when vision was available. For variability perpendicular to the direction of the movement, the spatial dispersion at peak deceleration was maintained until the end of the movement when vision was not available to guide the limb to the target, and there was a dramatic reduction in variability when the goggle lenses remained open. This pattern of spatial dispersion was more pronounced for small than for large targets and occurred regardless of how vision condition was scheduled (e.g., blocked, randomized, or alternating). This latter finding indicates that vision–no vision performance differences have more to do with the on-line utilization of visual feedback than between-trials feedforward influences. These data are also consistent with the notion that vision and no-vision trials may be prepared differently (Elliott & Allard, 1985) and that vision has its greatest impact during the final stages of the movement (Woodworth, 1899).

Another approach to dealing with the equivocal findings related to discontinuities in the trajectory has been to attribute them to prior planning processes rather than on-line control. Specifically, Plamondon (1995a, 1995b; Plamondon & Alimi, 1997) has challenged the idea that discontinuities in velocity and acceleration profiles reflect corrective processes based on the use of feedback. It is his view that the spatiotemporal characteristics of the movement trajectory, including what we have been calling *corrections*, are specified before the movement begins. The form of the trajectory is determined by the ratio of agonist and antagonist muscle commands. An important assumption of the model is that “sensory feedback is not used to control the trajectory” and that “feedforward control emerges through practice and learning” (Plamondon, 1995a, p. 296). This latter point seems to concede that although feedback may be needed during the first few attempts in a particular aiming situation, it will soon be replaced by open-loop processes that determine the nature of the movement prior to movement initiation (see Pew, 1966; Schmidt & McCabe, 1976).

Although Plamondon (1995a, 1995b) did an excellent job of describing how discontinuities can occur in the movement trajectory in the absence of corrective processes involving response-produced feedback, he never addressed the wealth of empirical work demonstrating that the availability of vision is one of the best predictors of movement accuracy (Carlton, 1992). Moreover, the importance of vision actually seems to increase, rather than de-

crease, with practice (see Proteau, 1992, and the Changes in the Control of Aiming Movements With Practice section later in this article). Although Plamondon also neglected to explain why the symmetry of movement trajectories varies based on availability of sensory information, his work does reinforce the point that the presence of a discontinuity in a trajectory does not necessarily mean a feedback-based correction has taken place (cf. Elliott et al., 1991; Meyer et al., 1988).

In summary, the kinematic evidence indicates that when vision is available, the initial portion of the movement is more stereotyped than the trajectory just prior to target acquisition. As the limb approaches the target, deceleration often occurs quite slowly, particularly if the accuracy requirements of the movement are high. As well, there are often (but not always) discontinuities in the deceleration profile that are taken to reflect discrete or more graded adjustments to the movement based on feedback (cf. Plamondon, 1995a, 1995b). These kinematic characteristics of the movement trajectory are consistent with the two-component processes for limb control identified by Woodworth (1899) more than 100 years ago.

Adjustments to the Movement Trajectory Following a Perturbation

Our examination of limb kinematics under different feedback conditions suggests that vision is used to both plan an initial movement impulse (i.e., off-line) and concurrently control a limb movement in progress (i.e., on-line). One of the reasons that on-line processes normally occur near the termination of the movement is that any error in the initial trajectory must be recognized before it can be corrected. In a normal target-aiming situation, the visual–motor system may not have the acuity to make the necessary motor adjustments based on small early errors (Elliott & Allard, 1985). Alternatively, the initial ballistic phase of the movement may have to run its course before adjustments, based on recognizable error, are even possible (Meyer et al., 1988). Presumably, those adjustments would be made on the basis of visual information gathered over at least some portion of that initial phase. One strategy researchers have used to dissociate prior planning processes from on-line control has been to unexpectedly change the movement requirements, forcing the system to adjust to the new movement requirements. Alternatively, it is possible to perturb the actual movement being performed. By introducing unexpected changes, the experimenter essentially eliminates any positive feedforward contribution to limb control in an attempt to examine the limits of the corrective process.

In a study designed to examine visual processing time, Elliott and Allard (1985) used lateral displacing prism spectacles with a randomly set base to induce very large movement errors (i.e., 15°). Participants viewed a single target with the prism spectacle in place and were required to move to the target in a variety of movement times. Because of the displacement, the prepared movement would have resulted in an average 15° error. On some trial blocks, visual feedback was eliminated on movement initiation. Without the opportunity to use visual feedback to correct the prism-induced error, participants were inaccurate regardless of movement time. When vision was available, however, participants recognized and corrected these errors unless they were moving very rapidly (in less than 140 ms). This estimate of visual pro-

cessing time was much shorter than a visual processing time calculated under similar circumstances without the prism spectacles. In the latter situation, early errors in the trajectory were relatively small and therefore more difficult to identify. Elliott and Allard concluded that early visual information about the movement trajectory is useful for limb control when it provides compelling information on movement error. Using a visual perturbation in which they delayed visual feedback about the limb's position in space, Smith and Bowen (1980) demonstrated that inaccurate visual feedback induces predictable movement errors even for very rapid target-aiming movements (i.e., 164 ms). In this case, early visual feedback disrupted target-aiming performance.

A number of researchers have reported that participants are able to rapidly adjust their movements to changes in the position of the target. Pélisson, Prablanc, Goodale, and Jeannerod (1986) had participants aim to targets with an unseen hand. When the target movements were of a small magnitude (2° to 4°) and occurred during a saccadic eye movement, participants were unaware that the target position had shifted, but they adjusted their movement trajectories to the new target position anyway. This adjustment process occurred without any movement time cost. Moreover, there was no evidence of a discrete adjustment to the movement trajectory. This can be taken as evidence for continuous on-line control of the movement trajectory and indicates that, at least within certain bounds, the initial movement impulse is amenable to adjustment. In this case, it was adjustment based on target information, and perhaps efferent and proprioceptive information about the movement of the limb and/or eyes, because the moving limb was never visible to the performer.

In a grasping study, Paulignan, MacKenzie, Marteniuk, and Jeannerod (1991) unexpectedly shifted the position of the target dowel to the right or left at the initiation of a discrete movement. Kinematic data collected from the wrist indicated that approximately 100 ms into the movement the original trajectory was aborted in favor of a movement path toward the new dowel position. These results indicate that the "initial impulse" or so-called ballistic phase of reaching and aiming movements may not be as predetermined as previously thought. Alternatively, the duration of this movement phase is very short (i.e., less than 100 ms). In either case Paulignan et al.'s results suggest that visual information about target position can be processed and used very rapidly (cf. Beggs & Howarth, 1970, 1972; Keele & Posner, 1968; Woodworth, 1899).

Recently, Heath, Hodges, Chua, and Elliott (1998) used a computer-based aiming task that allowed them to unexpectedly change the size (Experiment 1) or position (Experiment 2) of a target on movement initiation (see also Boulinguez & Nougier, 1999). This effectively changed the accuracy constraints imposed by the target. Of interest in these perturbed situations was whether movement time and the movement kinematics were a function of the initial target for which the movement was planned or the target that replaced it on movement initiation. Although the early kinematic markers such as peak velocity and time to peak velocity were dependent on the target size and movement amplitude associated with the original target, the time spent after peak velocity, and therefore overall performance, was determined by the accuracy demands imposed by the new target. In contrast to the Paulignan et al. (1991) and Pélisson et al. (1986) studies, this finding, and other work from our lab (Elliott, Lyons, Chua, Good-

man, & Carson, 1995), is consistent with the notion of two distinct movement phases—that is, an initial ballistic phase and a homing phase that is dependent on the new visual information. In the Heath et al. studies, the homing phase was characterized by a greater number of discrete corrections for final target sizes—positions that entailed a greater index of difficulty (see Fitts, 1954). Perhaps these sorts of discrete adjustments were needed because actual changes in the movement requirements made it necessary for the performer to modify the movement to a greater degree than would usually be necessary (see also Elliott, Chua, et al., 1995).

In another recent study from our lab, the target characteristics were kept constant and the actual movement was perturbed by unexpectedly changing the amount of muscular force required to propel the limb away from the home position toward the target (Elliott, Heath, Binsted, Ricker, Roy, & Chua, 1999). This was done using a steel aiming stylus and an electromagnetic plate as the home position. In a control situation, a 25 N force was required to overcome the magnetic resistance provided by the magnetic plate. On a small proportion of trials, the magnetic resistance was either eliminated completely or increased to 40 N. The idea was to create a situation in which a planned movement was either too forceful or not forceful enough to reach the target located 33 cm from the home position. In an initial experiment, participants were able to adjust to the force perturbation very efficiently with only a small movement time cost in the high-resistance situation and no movement time cost in the zero-resistance circumstance. When vision of the limb and target were occluded on movement initiation, participants were able to maintain their movement times but made 50% more errors when vision was not available. The most interesting findings were related to the overall strategy participants adopted to deal with this difficult target-aiming experience. When vision was available, participants achieved higher peak velocities earlier in the movement. Presumably, they were attempting to get the limb to the target area as quickly as possible so that they would have more time to use visual feedback to achieve the final target position. Moreover, the primary movement usually undershot the target regardless of the magnet setting (undershoots = 60%, on target = 39%, overshoots = 1%). Corrective submovements were then used to bring the limb the final distance to the target. As mentioned earlier, it is our contention that trajectory errors that bring the limb up short of the target are less costly, in terms of both time and energy, than initial movements that overshoot the target.

Proteau and Masson (1997) took a novel approach to examining limb control in goal-directed aiming. Rather than perturbing the limb or the target on movement initiation, their strategy was to vary the characteristics of the background against which visual response-produced feedback was available. They used a computerized aiming task in which participants applied finger pressure on a force transducer in order to move a cursor from a home position on the left of a computer screen to a target position on the right side of the screen. In a first experiment, they induced a perturbation in which the visual background started to move from right to left on movement initiation (i.e., in a direction opposite to the cursor). This gave the impression of the cursor moving at a higher velocity than it actually was. Compared with unperturbed trials, on perturbed trials participants terminated their movements sooner than they should have, resulting in target undershoots. Although the findings were not quite as robust, Proteau and Masson found the opposite result over the first few trials in a second study in

which they moved the background in the same direction as the cursor. That is, participants moved a greater distance on perturbed trials than they did on unperturbed trials.⁹ Presumably, this was because they judged the velocity of the cursor to be less than it really was. Because, with visual feedback, a performer can adjust for undershoots with second accelerations and for overshoots with movement reversals, Proteau and Masson used a movement termination criterion that captured the end of the primary movement, before discrete corrective movements had a chance to occur. Thus, the visual perturbation affected the control processes responsible for the primary movement. Once again, it would appear that this so-called ballistic phase of the movement is not so ballistic after all. Specifically, the perceived velocity of the effector allows for the on-line regulation of the movement trajectory enough to have a reliable impact on movement amplitude. Recall, this occurred before any discrete corrections had an opportunity to be realized. Unfortunately, Proteau and Masson did not examine the kinematic characteristics of the corrective process to determine the impact of their manipulation on the homing phase of the movement.

Although dealing with the neurophysiological correlates of limb control is beyond the scope of this review, it has been well established that posterior parietal cortex plays an important role in the visual regulation of movement (for a review, see Milner & Goodale, 1995).¹⁰ Desmurget et al. (1999) recently used a perturbation paradigm that provides unique insight into the on-line regulation of movement. Following procedures similar to Pélisson et al.'s (1986), participants made movements with an unseen hand to visual targets that either remained stationary or were moved slightly during a saccadic eye movement. Under normal circumstances participants adjusted their movement trajectories very rapidly to meet the demands imposed by the target's new position. In some situations, however, the experimenters applied transcranial magnetic stimulation over posterior parietal cortex contralateral to the aiming hand. When stimulation was applied to this specific region, corrections to the movement trajectory failed to occur. It would appear that this cortical region is at least partly responsible for the homing phase of the movement.¹¹

In summary, perturbation studies conducted in our lab (e.g., Elliott, Heath, et al., 1999; Heath et al., 1998), and elsewhere (e.g., Pélisson et al., 1986), again provide evidence for two-component processes in goal-directed movement. A prestructured portion of the movement is sensitive to the initial task requirements, but on-line modulation of the initial movement, based on response-produced feedback and/or unexpected changes to the task requirements, contributes to the movement's successful conclusion. Although the majority of the perturbation evidence fits nicely with two-component ideas about limb control, Proteau and Masson's (1997) indicates that the so-called initial impulse may be amenable to change through some type of continuous on-line process. This intriguing possibility opens the door for a whole new realm of model building.

Changes in the Control of Aiming Movements With Practice

One of the oldest assumptions about closed motor skills, such as aiming, is that with practice, a performer "progresses" from a feedback-based mode of control to a more centrally driven, feed-

forward mode of control that is less dependent on afferent information available during the actual execution of the movement.¹² Presumably, after repeated attempts at the same movement, the performer develops a central representation of the pattern of muscle activation required to bring the movement to a successful conclusion. Although the development of this central representation, or motor program, is dependent on adequate trial-to-trial feedback about performance, it eventually can be executed independent of on-line feedback (Keele, 1968; Schmidt, 1976). This view of the nature of limb control is intuitively appealing, but it is at odds with a number of studies on aiming and practice that have demonstrated that a large part of motor skill development involves learning to use on-line afferent information rapidly and efficiently.

The strongest evidence for the role of feedback in well-practiced movements comes from a number of aiming studies conducted by Proteau and his colleagues (for a review, see Proteau, 1992). In an initial study, Proteau, Marteniuk, Girouard, and Dugas (1987) had participants practice the same aiming movement either 200 or 2,000 times. Half the participants in each group had full visual feedback available during their aiming attempts, whereas for the other performers, vision of the arm and hand were eliminated on movement initiation. Following acquisition, all participants were required to perform the task in the no-vision circumstance. Although the traditional wisdom holds that the participants with 2,000 trials should be less affected by the removal of vision than people in the 200-trial group, these individuals actually exhibited a greater increase in target-aiming error when vision of the limb was prevented. This result indicates that people become more dependent on the feedback available to them during practice as training progresses (see also Elliott & Jaeger, 1988; Proteau, Marteniuk, & Lévesque, 1992). Certainly, this type of finding creates difficulty for models of limb control that minimize the overall importance of response-produced feedback (e.g., Plamondon-

⁹ Although the background manipulation was in the predicted direction, participants actually undershot the target with their primary movement in both the perturbed and the unperturbed situations. Proteau and Masson (1997) attributed this to a boundary effect related to the position of the target on the screen (Buck, 1976). It may, however, be due to the strategic tendency to undershoot rather than overshoot targets with the primary movement, because of the temporal and energy costs associated with the latter type of error (for a review, see Elliott, Binsted, & Heath, 1999).

¹⁰ Recent animal and human work indicates that the visual pathways from primary visual cortex to posterior parietal cortex (i.e., the dorsal stream) may be instrumental in the type of rapid, automatic limb control seen in many of the perturbation studies. The ventral stream (visual cortex to inferotemporal cortex), on the other hand, has been shown to be more important in more explicit visual decision-making that requires conscious, perhaps verbal, mediation.

¹¹ The authors also applied the stimulation at several control locations with no impact on the corrective process.

¹² Woodworth (1899) stated that improvement with practice was a function of changes in both the initial impulse and the current control phase of the movement: "The path to skill lies in increasing the accuracy of the initial adjustment, so that the later groping need be only within narrow limits; and through increasing the speed of the groping process, so that finally there seems to be no groping at all" (p. 59). The last part of his description appears to imply a progression from discrete to more continuous current control.

don, 1995a, 1995b; Schmidt et al., 1979). Of course, it is difficult to determine solely on the basis of performance data whether the advantages associated with visual feedback are the result of more efficient on-line control or the development of more effective feedforward processes whereby visual feedback from trial N facilitates trial $N + 1$ (see Henderson, 1977).

For the purposes of evaluating dual-process models of limb control (e.g., Meyer et al., 1988; Woodworth, 1899) and the relative importance of feedback and feedforward processes, it is instructive to examine the changes in movement kinematics that occur with practice. For example, Abrams and Pratt (1993) showed that participants are able to reduce their movement time over repeated aiming attempts not by altering the ballistic component of the aiming movement or by reducing the number of corrective submovements but by reducing the time spent to complete each corrective submovement. Abrams and Pratt concluded that practice "enhanced the ability to use feedback information" (p. 288).

Work from our lab indicates that over practice with full vision, a performer will often adjust the nature of the initial movement to make more time available for visual feedback utilization late in the movement. Specifically, participants learn to achieve higher peak velocities proportionally earlier in the movement (Elliott, Chua, et al., 1995; Elliott et al., 1997; Khan & Franks, 2000). This has the effect of bringing the limb into the target area more quickly, thus allowing more time for the homing phase. Sometimes this change in the trajectory of the initial movement is accompanied by a decrease in the number of significant deviations in the acceleration profile following peak velocity (Elliott, Chua, et al., 1995; Elliott et al., 1997). Although one might interpret this finding as evidence for more open-loop control, this notion is incompatible with transfer findings indicating that a change in the afferent conditions causes participants to adjust their movement trajectories to optimize the use of feedback in the new circumstance (see also Elliott, Ricker, & Lyons, 1998). The reduction in the number of corrections with practice could reflect the use of a more efficient, continuous form of visual regulation (see Elliott, Binsted, & Heath, 1999; Elliott et al., 1991).

Recently, Khan, Franks, and Goodman (1998) examined changes to the kinematics of aiming over more than 2,000 trials. Like Proteau et al. (1987), they reported that the withdrawal of vision was more detrimental to performance after extensive than after moderate practice. Their kinematic data indicated that learning involves both an improvement in the organization of the initial impulse (see also Pratt & Abrams, 1996) and an improvement in the feedback-based error correction process. As in previous work, the initial impulse usually undershot the target. However, as practice progressed, the distance traveled during the initial impulse gradually increased. This had the effect of reducing "the percentage of movements that contained an error correction phase" (Khan et al., 1998, p. 432). Although this finding alone could be taken for a shift from closed-loop to open-loop control, Khan et al. also developed an index of error-reducing effectiveness, taking into account error at the beginning and the end of a correction. On trials in which a correction occurred, the effectiveness of the corrective process improved with practice. Moreover, corrections with vision were much more effective than corrections in situations in which vision was eliminated on movement initiation. Thus, Khan et al.'s results not only support a dual-process model of limb control, but

they also indicate how the two-component processes both improve with practice.

Interestingly, when vision was withdrawn from participants after extensive practice, there was an increase in the spatial variability of the primary movement endpoint (Khan & Franks, 2000). Although this finding could be taken to reflect the early on-line (perhaps continuous) use of vision during the primary movement (e.g., Proteau & Masson, 1997), it could also reflect the role that visual feedback from one trial plays in organizing the initial impulse for the next trial (see Henderson, 1977). As Ghez et al. (1995) pointed out, visual feedback about the relative positions of the limb and target during movement may be needed quite frequently in order to calibrate other sensory and motor systems (e.g., proprioception).

In summary, recent motor learning work is consistent with the notion that there are two-component processes to goal-directed aiming. To improve aiming speed and accuracy, performers adapt their movement trajectories to make maximal use of the on-line and trial-to-trial sensory information available. This typically involves getting to the target area quickly (without overshooting it) in order to have sufficient time to use feedback to correct error. Thus, with practice, a performer becomes better at both structuring the appropriate initial impulse and using on-line feedback to rapidly correct any error inherent in the movement trajectory. When vision is present, it serves both a feedforward and feedback function.

Eye-Hand Coordination and Dual-Process Models of Limb Control

Surprisingly, most dual-process models of limb control were developed without reference to eye movements and eye-hand coordination in manual aiming. This is partly because, in a discrete aiming situation in which the target location is known in advance, the eyes fixate the target location long before a hand movement is initiated. This provides the performer with foveal information about the position of the target and often information from peripheral vision about the position of the hand. The hand moves into central vision as it approaches the target, and perhaps that is the reason why late visual information appears to be most important for limb control (Carlton, 1981a, 1981b; Chua & Elliott, 1993).

Of course, there are many situations in which the target location is not known in advance or, in the case of serial movements, circumstances that require the eyes to move from one target to another. Like limb movements, the endpoint variability of a set of saccadic eye movements depends on the forces required to generate those movements. Thus, spatial variability increases linearly with the average distance and duration of the saccades toward particular target positions (Abrams, Meyer, & Kornblum, 1989). Although it is instructive to know that the two effector systems are governed by some of the same motor control principles, under normal circumstances, it is the limb, not the eye, that must achieve a specific degree of precision. Thus, in the context of dual-process models of limb control, it is important to understand how eye movements constraint and/or facilitate the pickup of information necessary for corrective processes that occur as the limb approaches the target.

In a recent study, we examined eye–hand coordination in a situation in which participants fixated the home position and then made a 40-cm lateral movement to a small target when the home position was illuminated (Helsen, Elliott, Starkes, & Ricker, 1998). The hand trajectory was similar to what has already been described (e.g., Chua & Elliott, 1993). Specifically, on the majority of the trials, an initial movement undershot the target by 1 to 3 cm (i.e., 92% to 98% of the distance). A second, and sometimes a third, acceleration then brought the hand the final distance to the target. Total movement time and, in fact, total response time were highly correlated with the time spent after peak velocity, but not limb initiation time or the time spent before peak velocity.

More instructive in terms of the two-component model was the pattern of eye movements. On more than 99% of the trials, eye movements were initiated before hand movements (see also Prablanc, Echallier, Komilis, & Jeannerod, 1979).¹³ Because the duration of the first saccade was only 20% of the duration of the hand movement, the eye arrived in the target area during the early stages of hand movement, about the time the hand was achieving peak acceleration (see also Abrams, 1992; Abrams, Meyer, & Kornblum, 1990). Like the hand movements, the initial saccade usually fell short of the target (i.e., 2° or 3°; Vercher, Magenes, Prablanc, & Gauthier, 1994; cf. Carpenter, 1988, for short amplitude saccades). In the majority of instances (79%), the initial saccade was followed by a short-latency corrective saccade that brought the eyes onto the target. In this experiment, the order of termination of point of gaze and hand movement was 100% reliable. The eyes always arrived first, at approximately the same time the hand achieved peak acceleration (see also Carnahan & Marteniuk, 1991, 1994). This allowed plenty of time for the pickup of visual information about the hand and target positions on which to base changes in the limb's trajectory.

As Abrams (1992) pointed out, the eyes have the potential to provide other important information for the control of the limb movements toward a fixed target location. For example, because eye movements are usually initiated before limb movements, and always finish first, the hand has the potential to benefit from both efferent information about the central commands required to move the eyes to the target area and afferent information about the final position of the eyes and head. Along with vision of the hand and the target, this information may contribute to the corrective process (Prablanc, Echallier, Jeannerod, & Komilis, 1979). In a series of studies, we have used the Muller–Lyer illusion to bias eye movements during target-aiming in order to determine if compromised extraretinal information about the movement and position of the eyes impacts on the endpoint accuracy of the hand (Binsted, Chua, Helsen, & Elliott, 2000; Binsted & Elliott, 1999). Interestingly, biased extraretinal information about target position had an impact on hand performance only when visual information about the position of the target was eliminated on movement initiation. Rather than being a slave to the eye, or being governed by the same movement commands (e.g., Biguer, Jeannerod, & Prablanc, 1982; Bizzi, Kalil, & Tagliasco, 1971), the hand appears to be more accurate than the eyes; that is, the hand benefits from visual information provided by the eye (see Carey, 2000) without being subject to a number of perceptual biases (Aglioti, Goodale, & DeSouza, 1995; Binsted & Elliott, 1998, 1999; cf. Proteau & Masson, 1997).

Woodworth's Two-Component Model Updated

After a century, Woodworth's (1899) two-component model of limb control still provides an important foundation for much of the work designed to explain speed–accuracy relations and visual control in goal-directed movement. Of theoretical significance has been progress in describing the relation between intensity of the initial movement impulse and the spatial variability of the limb's trajectory (e.g., Meyer et al., 1988; Schmidt et al., 1979).¹⁴ More than anything, it is the lawful relation between the magnitude of the initial impulse and the dispersion of primary movement endpoints that defines the extent to which corrective processes (current control) must operate. Following Woodworth (1899), the empirical work over the past century has demonstrated that there is no reliable substitute for on-line visual information about the relative positions of the limb and the target if limb movements are to achieve a consistent degree of accuracy (for a review, see Elliott, Binsted, & Heath, 1999).

Although the optimized submovement model (Meyer et al., 1988, 1990) provides the best contemporary description of central and peripheral contributions to precision upper limb control, in this review, we have identified several principles that have to be incorporated into current explanations of speed–accuracy relations. First of all, there is an abundance of empirical evidence to indicate that distributions of primary movement endpoints are seldom centered around the middle of the target (cf. Meyer et al., 1988). Taking into account that movement planning is subject to error (Schmidt et al., 1979), as well as anticipating the impact of neural-motor noise on execution (Meyer et al., 1982), the initial “ballistic” movement is organized in a manner designed to minimize the temporal costs associated with error in the initial trajectory (Guiard, 1993). In most two-dimensional and three-dimensional aiming situations, target overshoots will be more time-consuming than target undershoots (Elliott et al., 1991). This is because the limb must travel a greater overall distance. Increased distance means increased time. As well as the extra distance traveled to reach the target, an overshoot requires a movement reversal. For a movement reversal, the limb must overcome the inertia of a zero-velocity situation. Also, a reversal requires a change in the role of the muscle groups involved in the limb movement (i.e., the agonist become the antagonist and vice versa). The former situation results in both a temporal and an energy cost (Guiard, 1993), and the latter requirement introduces increased attention demands (Brebner, 1968). Although factors such as the

¹³ Under some target conditions, hand movements are sometime initiated before eye movements (e.g., Carnahan & Marteniuk, 1991). What does appear to be invariant across studies is movement termination on or around the target. Specifically, the eyes arrive in the target area well in advance of the hand (Carnahan & Marteniuk, 1991, 1994; Helsen, Starkes, Elliot, & Ricker, 2000), regardless of the distance covered (Helsen, Starkes, & Buekers, 1997).

¹⁴ Although Woodworth (1899) argued that the impact of movement speed had its primary effect on the current control phase of the movement, he did concede that the initial adjustment could be influenced as well. His premise was that increased speed could negatively affect movement timing: “A slight error in duration of a movement would mean a greater error in extent, when the velocity was greater” (p. 52).

mass of the effector¹⁵ and the plane of the movement (e.g., the role of gravity) will mediate the temporal and energy cost associated with error in the initial impulse, it is our contention that, in order to optimize movement speed and movement accuracy, the distribution of primary movement endpoints will be centered around a location that is short of the target.¹⁶ Ideally the tail of the distribution will extend into the target area, but only a small proportion of the distribution will extend beyond the actual target area (see Elliott, Heath, et al., 1999).

The second set of evidence that has to be incorporated into dual-process models of speed-accuracy relations and limb control concerns the changes that take place in manual aiming over practice. As researchers, we have been naive to assume that the performer comes to a particular task situation aware of the inherent variability associated with a specific class of movement. We have shown that, as a performer becomes more practiced at a particular aiming task, several changes occur that are designed to minimize movement time while maintaining movement accuracy (Elliott, Chua, et al., 1995). Specifically, the initial impulse becomes more forceful, resulting in higher peak velocities and acceleration achieved earlier in the movement. In isolation this increase in accelerative force should result in increased force variability and increased endpoint error (Schmidt et al., 1979). However, it also has the effect of getting the limb to the target area more rapidly. Thus, the performer has a shorter movement time while maintaining the same real time (and greater proportional time) for feedback-based correction. Although there will always be neural-motor noise for the system to deal with, repeated attempts at the same movement also allow the system to discover how close the limb can get to the target with the initial impulse while maintaining a low risk of overshooting the target (Khan et al., 1998). This trial-to-trial discovery process, along with more efficient continuous regulation, may be responsible for the decrease in the number of corrective submovements, but not the dependence on vision, sometimes seen after extended practice (e.g., Elliott, Chua, et al., 1995; Elliott et al., 1997).¹⁷ Learning then involves changes to both central and feedback-based processes (Woodworth, 1899).

It would be straightforward to add corollaries to current dual-process models of limb control (e.g., Meyer et al., 1988) to deal with practice effects and the relative merits of undershooting or overshooting the target with the initial impulse. However, a body of evidence is beginning to emerge indicating that the initial impulse and current control may not always be independent. Although the forces associated with agonist muscle activity appear to be less amenable to on-line regulation (Heath et al., 1998), the muscular forces used to brake the movement can be adjusted based on dynamic information about the velocity of the moving limb (Proteau & Masson, 1997). This regulation can be accomplished through cocontraction of the agonist muscle group along with the graded activation of the antagonist group. This corrective process can occur in the absence of discrete discontinuities in the velocity and acceleration profiles (Elliott, Binsted, & Heath, 1999). This may be what Woodworth (1899) referred to as "subtraction" (p. 58), and it is one type of feedback-based homing.¹⁸ Within limits, this type of continuous visual regulation appears to be possible even when the limb movement or the target position is perturbed. It is probably the case that continuous visual regulation occurs most often in isolation when the difference between the desired and the required initial impulse is small (Elliott, Heath, et al.,

1999). Continuous regulation is characterized by asymmetric velocity-acceleration profiles (i.e., greater proportional time after peak velocity), particularly when the accuracy demands of the movement are high. Future models of speed-accuracy relations in goal-directed movement should incorporate mechanisms-processes for graded limb control during deceleration.

Summary

R. S. Woodworth's (1899) doctoral dissertation, published as a monograph by *Psychological Review*, has been of tremendous importance to researchers interested in human performance and learning. Woodworth's primary research strategy involved applying the principles and methods used to study human perception to the study of voluntary movement. Although his empirical work related to motor memory, motor learning and fatigue, and kinaesthetic and visual feedback processes in limb control made important additions to the existing literature, it is really his theoretical contribution to our understanding of speed-accuracy relations and the control of rapid goal-directed movements that has stood the test of time. In his monograph, Woodworth offered a framework that has been used to guide experimentation into target-directed movements over the past century. Researchers interested in the control of limb movements have studied, in detail, movement planning, corrective processes, time to process feedback, impulse variability, and so forth in attempts to further elaborate the control processes that underlie the two components of aiming movements first identified by Woodworth. A consequence of the empirical attempts to understand the specific principles that govern the "initial impulse" and "current control" has been the development of more elaborate models of limb control. Many of these models (e.g., Meyer et al., 1988) make very specific predictions about movement kinematics and outcomes that can be tested empirically. The process of prediction and experimentation has allowed researchers to fine-tune the two-component description of limb control that Woodworth first provided. In this article, we have reviewed some of the progress we have made over the last hundred years, as well as identified several issues that are yet to be addressed.

¹⁵ Following this logic, greater undershooting would be expected in three-dimensional aiming situations that involve movement of the whole arm (e.g., Elliott et al., 1991) than in one-dimensional computerized aiming that, for example, involves a wrist rotation to displace a cursor on a monitor (e.g., Meyer et al., 1988).

¹⁶ Worringham (1991) showed that undershooting increases with the variability of the initial impulse. This reflects a "play-it-safe" strategy.

¹⁷ This type of learning-discovery process has some similarity to the procedures used by the performer to find the safe-fast responding zone in serial reaction time tasks (e.g., Rabbitt, 1981).

¹⁸ The second type of corrective process Woodworth (1899) identified was "later adjustments" (p. 54). These are equivalent to what we have been calling *discrete corrections*. As discussed earlier, this process involves discrete second, third, and sometimes fourth submovements (Crossman & Goodeve, 1983; Meyer et al., 1988, 1990). Because the cost minimization strategy associated with the initial impulse generally results in a target undershoot, discrete corrections usually take the form of second accelerations that propel the limb the extra distance to the target area. Although the early portion of these secondary submovements may be programmed, there is every reason to suspect that their deceleration can be accomplished in a continuous manner as well (Proteau & Masson, 1997).

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