Acta Psychologica 163 (2016) 27–37

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Common vs. independent limb control in sequential vertical aiming: The cost of potential errors during extensions and reversals

James W. Roberts [a,*], Digby Elliott [b,a], James L. Lyons [a], Spencer J. Hayes [b], Simon J. Bennett [b]

[a] Motor Behaviour Laboratory, Department of Kinesiology, McMaster University, Hamilton, ON L8S 4L8, Canada
[b] Brain and Behaviour Laboratory, Liverpool John Moores University, Liverpool L3 3AF, UK

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 22 April 2015
Accepted 26 October 2015
Available online 18 November 2015

PsycINFO classification:
2330

Keywords:
Sequential aiming
Movement optimization
Feedforward
Feedback

ABSTRACT

The following study explored movement kinematics in two-component aiming contexts that were intended to modulate the potential cost of overshoot or undershoot errors in up and down directions by having participants perform a second extension movement (Experiment 1) or a reversal movement (Experiment 2). For both experiments, the initial movement toward a downward target took longer, and had lower peak acceleration and peak velocity than upward movements. These movement characteristics may reflect a feedback-based control strategy designed to prevent energy-consuming limb modifications against gravitational forces. The between-component correlations of displacement at kinematic landmarks (i.e., trial-by-trial correlation between the first and second components) increased as both components unfolded. However, the between-component correlations of extensions were primarily negative, while reversals were positive. Thus, movement extensions appear to be influenced by the use of continuous on-line sensory feedback to update limb position at the second component based on the position attained in the first component. In contrast, reversals seem to be driven by pre-planned feedforward procedures where the position of the first component is directly replicated in the second component. Finally, the between-component correlations for the magnitude of kinematic landmarks showed that aiming up generated stronger positive correlations during extensions, and weaker positive correlations toward the end of the first component during reversals. These latter results suggest the cost of potential errors associated with the upcoming second component directly influence the inter-dependence between components. Therefore, the cost of potential errors is not only pertinent to one-component discrete contexts, but also two-component sequence aims. Together, these findings point to an optimized movement strategy designed to minimize the cost of errors, which is specific to the two-component context.

1. Introduction

The two-component model of goal-directed aiming (Woodworth, 1899), and subsequent extensions of this model (Elliott, Helsen, & Chua, 2001), suggest manual aiming consists of two distinct phases: an *initial impulse* designed to place the limb within the vicinity of the target, followed by a slowed *current control* phase designed to 'home-in' on the target by using online sensory feedback. According to the optimized submovement model (Meyer, Abrams, Kornblum, Wright, & Smith, 1988), these movement phases are coordinated so as to optimize the relationship between variability associated with ballistic movements (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979) and the time-consuming error corrections designed to successfully land on the target. A central tenet of this optimization is that the initial submovement endpoints of goal-directed aims form a normal distribution centred on the middle of the target (Meyer et al., 1988). Although this outcome may hold for movements requiring minimal force over smaller displacements and with limited degrees-of-freedom (wrist rotation task), it appears that for the initial primary submovement endpoint for whole-limb movements, featuring coordination of the shoulder, elbow and wrist, there is a more strategic spatial displacement of primary submovement endpoints. That is, individuals typically undershoot the target, and with trial-and-error practise, begin to coincide decreases in variability with longer movement displacements closer to the target ("sneaking-up"; Elliott, Hansen, Mendoza, & Tremblay, 2004; see also Worringham, 1991). This strategic approach reduces the potential temporal and energy costs associated with correcting a target overshoot. That is, the performer would require more time and energy to overcome the inertia associated with a zero-velocity situation at the point of a reversal.

The tendency to minimize energy was demonstrated by assisting movement of the limb via an attached elastic rubber band that required greater eccentric force to maintain the start position. In this condition, individuals begin to overshoot the target as undershooting required more effort (Oliveira, Elliott, & Goodman, 2005). However, upon removing the assistive band, presenting a more typical unassisted condition,

---

* Corresponding author.
E-mail addresses: robjames@mcmaster.ca (J.W. Roberts), d.elliott@ljmu.ac.uk (D. Elliott), lyonsjl@mcmaster.ca (J.L. Lyons), s.hayes@ljmu.ac.uk (S.J. Hayes), s.j.bennett@ljmu.ac.uk (S.J. Bennett).

http://dx.doi.org/10.1016/j.actpsy.2015.10.004
0001-6918/

individuals once more begin to undershoot the target. Examining a similar energy-minimizing principle, Lyons and colleagues (Lyons, Hansen, Hurding, & Elliott, 2006) had participants aim within horizontal and vertical axes so as to manipulate the gravitational forces acting upon the limb. It was shown that when aiming in the downward (vertical) direction individuals achieved a lower peak velocity and a shorter primary submovement endpoint compared to the upward direction. The tendency to exhibit less force and undershoot the target when aiming downward was suggested to reduce endpoint variability and prevent a target overshoot that would subsequently require corrections against gravity. This contrasted with overshoots in the upward direction, which although less time-efficient and more energy-consuming than undershoots, required error corrections in the direction of gravity.

Although the control of aiming to a single target (i.e., discrete one-component tasks) has been considered in light of principles of energy-minimization, it remains unclear whether or not the same constructs apply to multiple-component sequence aiming. To date, it has been shown that the addition of a second target results in a longer initiation time, reflecting the time necessary to programme the additional component (Henry & Rogers, 1960; Khan, Lawrence, Buckolz, & Franks, 2006). Furthermore, it has been shown that the spatial characteristics (Adam, van der Buggen, & Bekkering, 1993; Sidaway, Sekiya, & Fairweather, 1995) and sensory information (Lavrysen, Helsen, Elliott, & Adam, 2002; Ricker et al., 1999) associated with the later component can have overriding consequences on how individuals prepare and execute movements within earlier portions of the sequence (i.e., inter-dependency). These findings have led to suggestions that sequential aiming movements are a pre-planned composition of individual components that are released during movement execution (Adam et al., 2000). Thus, the integration of multiple components within a sequence changes underlying sensorimotor processing, and with that, the unfolding movement trajectory compared to more discrete one-component aims. This, in turn, may alter the costs associated with correcting certain types of end-point errors. For instance, in the context of two-component extension aims in the vertical axis, an overshoot at the first target may result in a costly movement reversal if the participant compensates by reducing the amplitude of the second component. Therefore, the preparation of a second movement component may alleviate the cost of overshoot errors at the first target. That is, the limb may be prepared for a second movement component following completion of the first, without comprehending the need for time- and energy-consuming corrections. Alternatively, for one-component aims, we would expect a series of slowed mechanical oscillations designed to offset the limb at target position, and thus a greater need to consider the cost of an overshoot.

2. Experiment 1

2.1. Introduction

To examine how the tendency to minimize potential errors during goal-directed aiming influences sensorimotor processing and control, we had participants execute a series of aims that either alleviated or exacerbated the cost of potential errors by way of moving up and down in one- and two-component contexts. We reasoned that overshoot errors in the typical one-component context would be more costly for moving down than when moving up due to the required corrections working against gravitational forces acting on the limb (Lyons et al., 2006). Moreover, based on the notion that the cost of overshoot errors is reduced when the direction of overshoots (e.g., down) correspond with the movement direction to the second target (e.g., down), we expected that the impact of movement direction would be modulated as a function of the number of movement components. More specifically, we predicted movement kinematics featuring a higher initial impulse, as indicated by a greater magnitude of peak acceleration and peak velocity, and a longer movement displacement, during two-component trials compared to one-component trials, and that these differences in magnitude and displacement would be exaggerated when moving down as opposed to up. In addition, given the integration of multiple-component movements is dependent upon the spatial characteristics that are the sum of its component parts (see Khan, Helsen, & Franks, 2010), we explored the relationship between components of the two-component sequences as a function of moving in the up and down direction.

2.2. Method

2.2.1. Participants

Fifteen males and one female from Liverpool John Moores University (age range = 20–30 years, height $M = 178.5$ cm $SD = 8.5$ cm), agreed to take part in the study. All participants were self-declared right-handed, and had normal or correct-to-normal vision with no history of neurological disorders. The study was designed and conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

2.2.2. Apparatus and procedure

The apparatus consisted of a wall-mounted LCD monitor (54-cm diagonal; 154 cm from ground-to-screen centre) with a spatial resolution of 1600 × 1200 pixels, and refresh rate of 85 Hz. The visual stimuli were generated in MATLAB (The Mathworks, Inc) using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/cogent.php). Participants stood directly in front of the stimulus display, which was covered with a sheet of 5-mm thick transparent Plexiglas. An infrared emitting diode (IRED) was attached the tip of the dorsal side of the distal phalange of the right index finger. Finger-tip position was recorded using a 3D Investigator Motion Capture System (Northern Digital Inc., Ontario, Canada) sampling at 200 Hz. Prior to each trial, participants were instructed to prepare their arm posture by positioning the index finger over a grey home position at screen centre. Following a random foreperiod (200–800 ms), one or two red targets (10 mm) were presented for a period of 2000 ms. At the end of a trial the target(s) was extinguished, and participants relaxed the limb by returning it to their side for an inter-trial interval of 5000 ms. In one-component trials, only a single target was presented at 80 mm (near) or 160 mm (far) above or below the home position (Fig. 1A). For two-component trials, two targets, one at 80 mm and the other at 160 mm, on the same side of the home position were presented simultaneously in either the above or below location. In the event of a single target presentation, participants were instructed to execute a one-component aimed response as fast-and-accurate as possible. For the appearance of two targets, a two-component sequential aimed response was required involving an immediate arm movement extension after completion of the aiming movement toward the first target. In all aiming conditions, participants were required to move to the target(s) without keeping the limb in contact with the aiming surface (i.e., without sliding). There were 10 blocks of 12 trials, consisting of 20 trials per condition. There were 6 conditions, formed from the combination of direction, target distance and component (upward near one-component, downward near one-component, upward far one-component, downward far one-component, upward two-component, downward two-component). The 6 conditions were randomly presented twice within each block under the caveat that no single combination could appear on two consecutive trials.

2.2.3. Dependent variables and analysis

Three-dimensional position data were filtered using a second-order Butterworth filter at a low-pass cut-off frequency of 8 Hz. Data were then differentiated and double-differentiated to obtain velocity and acceleration within the primary movement (y) axis. Movement onset was determined when velocity was above +10 mm/s for upward movement and below −10 mm/s for downward movement, and remained so for at least 40 ms (8 consecutive samples). Movement offset was determined by the first moment velocity was less than +10 mm/s for