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Manual coordination with intermittent targets: Velocity information for prospective control

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ABSTRACT

Tracking a moving target requires that information concerning the current and future state of a target is available, allowing prospective control of the tracking effector. Eye movement research has shown that prospective visual tracking is achievable during conditions of both visible and occluded targets. The ability to track visually occluded targets has been interpreted as individuals integrating target velocity into eye movement motor plans. It has not been fully established that velocity plays a similar role in other types of tracking behavior. To examine whether target velocity is also used in manual tracking, numerical predictions and a validation experiment were conducted. Predictions indicated that, if individuals utilize target velocity during coordination, increases in visual occlusion periods should yield increased phase lag between target and hand, proportional to the occlusion period. Predictions also suggest that increased occlusion yields increased coordination variability. An experiment having participants coordinate with the same stimuli and occlusion conditions was conducted to verify the predictions. Comparison of prediction and experimental results provides strong agreement that individuals use target velocity to prospectively control coordinated movements.

1. Introduction

Perceptual–motor coordination underlies many everyday tasks, such as catching a falling baseball (Oudejans, Michaels, Bakker, & Dolne, 1996), tapping to a beat (Repp, 2005), or moving with another person (Fine & Amazeen, 2011; Schmidt & Richardson, 2008). Such coordination cannot be purely reactive; tasks such as catching a ball (Oudejans et al., 1996) and passing through a closing door (Fajen et al., 2011) require perceiving information that specifies how a person should move to get to the right place, at the right time (Fajen, Riley, & Turvey, 2009; Turvey, 1992). The necessity of prospective, non-reactive coordination is particularly obvious in situations when the target is sporadically occluded (Amazeen, Amazeen, Post, & Beek, 1999; Barnes & Asselman, 1991; Morgan & Turnbull, 1978) — for example when a hunter is tracking his prey in a forest. Periodic occlusion is commonly used as a method to investigate the information used in visual tracking. These experiments have identified target velocity as a potential source of information (Barnes & Asselman, 1992; Churchland, Chou, & Lisberger, 2003; Orban de Xivry, Missal, & Lefevre, 2008). Although prospective information is also necessary for manual (hand) coordination with a target, similar experiments have not been conducted. The present experiment tests the hypothesis that target velocity is similarly used during manual tracking to maintain coordination with a regularly occluded target.

1.1. Information for coordination: eye-tracking

The ability to coordinate with a relatively low tracking error suggests that prospective information underlies visual coordination (Dallos & Jones, 1963). Using such information obviates neural delays in processing visual information and generating movements (Barnes, Barnes, & Chakraborti, 2000; Jordan, 1995; Vercher & Gauthier, 1992). To examine the effects of visual–motor delay on visual tracking, Barnes et al. (2000) had participants track a single-cycle of a sinusoidal target moving horizontally. With repeated presentations of a stimulus, participants accurately tracked the target. When catch trials were included — the target was supposed to appear but did not — pursuit eye movements were still initiated. Participants took 200–400 ms to correct their movements in catch trials; this time is in the range needed to detect an error and generate a new motor program. Catch trial movements exhibited a peak velocity and profile comparable to the expected stimulus motion. These findings suggest that the expected target's velocity is used to generate eye movements approximately 200–400 ms ahead of the current target position, bypassing visual–motor delays.

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In Barnes et al. (2000), eye movements matched the velocity profile of the expected but absent target. The disappearance of a tracked target is not always unexpected (Barnes & Asselman, 1992), for example, when a target passes behind a visible obstacle. Orban de Xivry et al. (2008) examined whether eye movements are similarly guided by target velocity when occlusion is expected. When the targets disappeared, eye movements maintained the target trajectory with a fair degree of accuracy (Churchland et al., 2003). Additionally, the ratio of retinal and target velocity was a close match till approximately 150–250 ms after occlusion (Becker & Fuchs, 1985; Churchland et al., 2003; Lisberger, Morris, & Tychsen, 1987). Similar to Barnes et al. (2000) and others (Barnes & Asselman, 1991, 1992; Orban de Xivry, Bennett, Lefevre, & Barnes, 2006), this result implicates target velocity as playing a substantive role in controlling tracking movements.

1.2. Information for coordination: manual-tracking

As discussed with reference to visual tracking, the presence of sensory-motor (Carlton, 1981) or artificial informational delays (Vercher & Gauthier, 1992) makes prospective information necessary for other forms of motor coordination, such as catching a ball. This is true whether a target is always visible (Michaels, Jacobs, & Bongers, 2006; Liao & Jagacinsku, 2000) or periodically occluded (Amazeen et al., 1999; Bosco, Delle Monache, & Lacquaniti, 2012). Some researchers (Dessing, Peper, Bullock, & Beek, 2005; Peper, Bootsma, Mestre, & Bakker, 1994) have proposed that individuals control movements for tasks such as manual interception by detecting the required velocity. The present experiment aims to test this hypothesis. Although this research is motivated by work in visual tracking literature, we are not implying that manual tracking is a direct analog.

Evidence for the role of target velocity in hand coordination was demonstrated by Buekers, Bogaerts, Swinnen, and Helsen (2000). Buekers et al. (2000) examined whether the continuity of a visual stimulus affected coordination stability. Participants coordinated hand movements with a visually continuous and an intermittent stimulus. The continuous stimulus was an LED that moved side-to-side across a light strip. The intermittent stimulus only appeared at the endpoints, analogous to a visual metronome. Coordination was indexed using relative phase ($\Phi = {}_{\text{person}} - {}_{\text{stimulus}}$), and coordination variability is the SD Φ. The endpoint variability of relative phase was lower with the continuous stimulus, indicating more stable coordination with continuous viewing. Despite the high predictability of the visual metronome — movement times between endpoints took the same amount of time as the continuous stimulus — coordination was impaired in this condition. The movement kinematics between endpoints suggests why. The only kinematic marker to show notable differences across conditions was the time to peak velocity in each cycle; participants were slower to reach peak velocity in the intermittent condition. This suggests that the information lost in the intermittent condition is related to the velocity profile of the movement needed to maintain coordination.

The work of Buekers et al. (2000) and others (Dessing et al., 2005; Peper et al., 1994; Michaels et al., 2006) suggests that target velocity plays a role in generating rhythmic hand movements. Perceptual variables regarding target movement are typically considered in a higher-order form (e.g., phase angle or time-to-contact; Bingham, 2004), derived from both a target's velocity and position. These variables jointly influence the control of coordination and tracking. Other studies, though, have invited a different conclusion (Brouwer, Brenner, & Smeets, 2002 or Smeets & Brenner, 1995). For example, Smeets and Brenner (1995) proposed that trajectory formation was driven by a target's expected position, while perceived velocity had no effect on trajectory formation with the result that velocity only affects movement timing. They (Brenner, Smeets, & de Lussanet, 1998; Smeets & Brenner, 1995) have concluded that both variables are independently controlled by the perceptual–motor system.

1.3. Experiment and predictions

Individuals clearly use target information for manual tracking and coordination. Target interception studies have garnered findings suggesting either independent control of target position and velocity (Smeets and Brenner, 1995), or a higher-order relationship (Dessing et al., 2005). A consensus is not possible from the current set of literature, likely due to differences in methodologies. Interception work typically involves discrete movements, with findings that might not extend to rhythmic tasks. Additionally, less work has examined how individuals guide manual tracking movements when target resolution is manipulated (cf. Buekers et al., 2000). It has been particularly revealing for studies of eye-tracking to consider control behavior under these types of visual conditions.

The purpose of the current work was to examine the roles of target information, particularly velocity, with differing target resolutions during manual tracking. To this end, we examined rhythmic, manual tracking. We hypothesized that when a target is visually unavailable, participants employ a hand speed with reference to the last perceived target velocity to maintain coordination. This prediction is based on the assumption that, when the target is not seen or unavailable, people update movement velocity based on the previously seen target; thus, movement velocity is not constant. To examine this proposal, we present numerical predictions regarding coordination (indexed by relative phase; Φ). The aim was to establish a relationship between coordination with respect to differences in stimulus variability and visual information. Experimental results are also presented after the numerical section, which provide good agreement with the predictions.

2. Methods

2.1. Numerical methods

Two 1 Hz (sampled at 75 Hz) sinusoidal motion signals (Fig. 1) were created, one with a constant amplitude and the other an amplitude that varied randomly from cycle-to-cycle. The signals were created using solution (2) for a simple harmonic oscillator (Eq. (1)):

$$\ddot{y} + Ky = 0 \tag{1}$$

$$y(t) = A(t)\sin(\omega t). \tag{2}$$

In Eq. (1), the double dot refers to the second derivative of position (acceleration). The parameter K is equivalent to the ratio of a stiffness

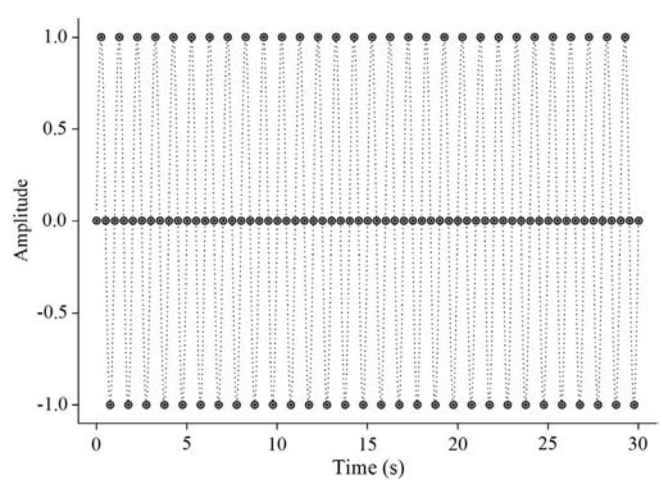

Fig. 1. Constant amplitude time series showing (circles) when the target was displayed in the cycle for the 250 ms display interval (ms) condition.