Exp Brain Res (2011) 214:631–644
DOI 10.1007/s00221-011-2865-y

RESEARCH ARTICLE

Locomoting-to-reach: information variables and control strategies for nested actions

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Received: 23 June 2010 / Accepted: 3 September 2011 / Published online: 20 September 2011

Abstract Locomoting-to-reach is a basic perception/action behavior that requires visual information for the control of both locomotion and reaching components. We investigated the visual information and the control strategies used to guide both the head and the hand on approach to a target in a locomotion-to-reach task. In this study, participants were required to locomote in the dark to a lit target in three different conditions: monocular vision/target with image size, binocular vision/target with image size, and binocular vision/point-light target (without image size). In task one, participants brought their eyes to the target. In task two, participants brought their outstretched hand to the target. Movement trajectories for both tasks were analyzed. Results show that participants were significantly more accurate when binocular information was present. In both tasks, participants were found to use a proportional rate control strategy rather than a constant $\dot{\tau}$ strategy. In the walk-to-reach task, they used monocular and/or binocular τ information to guide the head and then switched to using relative disparity τ to guide the hand to final target acquisition, switching when the hand centric τ became less than the head centric τ. Dynamical models of the information and control strategies were used to perform simulations that were found to fit the data well. The conclusion is that proportional rate control is used sequentially with head centric, then hand-centric τ-based information, using at each moment the τ with the smallest value.

Keywords Locomotion · Reaching · Proportional rate · Tau · Information · Locomotion-to-reach

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Introduction

Walking to reach for something is an action commonly performed many times a day, for instance, walking to open a door or to pick up a pan on the stove. Both the walking (locomotion) and reaching (prehension) components of this action have been studied often and independently by perception/action researchers but only a small number of studies have investigated the nesting of these two actions into a single, coordinated, whole-body behavior. The majority of previous research on locomoting-to-reach has examined the issues of biomechanical stability during the reaching phase (Bertram 2002; Carnahan et al. 1996; Cockell et al. 1995) and changes in walking behavior given changing task demands (Bertram 2002; Marteniuk et al. 2000, Marteniuk and Bertram 2001; Rosenbaum 2008; van der Wel and Rosenbaum 2007). These studies have established that, in locomoting-to-reach behavior, the prehensile action is nested in the locomotor action. Both prehensile and locomotor components are targeted actions. The locomoting observer must first move the body to within reaching distance of the target and then, as the target becomes sufficiently close, reach to the target location. However, this previous research has not addressed the central question for any perception/action task, namely what is the information and how is it used? The goal of the current work was to investigate what visual information and control strategy is used to guide locomoting-to-reach behavior. This task requires either information about each of the variables that define the kinematic relationship between observer and target (distance, velocity, etc.) or instead, some other informational variable that can serve to guide the actions directly to bring the actor to a stop within range of the target with the hand at the target. We will show that, for both the locomotion and prehensile components of the task, observers use the latter type of direct information variable.

Visually guided locomotion

Visually guided locomotion has been studied extensively, and current understanding of the organization of this action is as follows. Visual information structures control strategies that are used to guide targeted locomotion (i.e., Lee 1976; Fajen 2005). The information is used to control parameters of the action system. Motion of the body through space generates changes in optical structure that contains perceptual information used in turn to guide the actions being performed. Previous research has focused on two subtasks for visually guiding targeted locomotion, namely steering (including obstacle avoidance) and control of deceleration through braking. There are competing hypotheses about how optic flow structure is related to image structure and used to steer locomotion (Yilmaz and Warren 1995; Fajen 2005; Wann et al. 1993). In the current work, we address the other subtask, control of approach and braking.

Control of braking

Previous research has found support for two distinct theories of visually guided braking. In this paper, we introduce a third theory. The first theory is constant $\dot{\tau}$ control. Lee (1976) hypothesized that actors move so as to maintain a constant rate of change of monocular τ (e.g., image size divided by image expansion rate) at a value of -0.5. Moving in this way will bring the actor to a stop at the target location (i.e., soft contact at the target). The second theory is ideal deceleration. Fajen (2005) hypothesized that actors move so as to maintain a constant ideal deceleration using τ in combination with estimates of velocity drawn from global optic flow. A third theory is the proportional rate strategy. Anderson and Bingham (2010) hypothesized that actors move so as to maintain the rate of change of τ in proportion to τ itself to stop with soft contact at a target. In a proportional rate strategy, actors choose a proportional rate at which τ changes. Selecting various proportionalities will modulate the deceleration trajectories such that the actor can stop either more or less rapidly. This feature also provides stability in the face of perturbations to braking (e.g., the braking capability is not what was expected). In a proportional rate control strategy, both $\dot{\tau}$ and τ approach zero as the participant closes on the target location.

All of these control strategies rely on the use of the information variable τ. τ is an optical variable that can specify the time-to-contact of an object approaching the eye. One way to define τ is as the proportion between image size and image expansion rate. Lee (1976) formalized τ as:

$$\tau = \theta/(\mathrm{d}\theta/\mathrm{d}t),$$

where θ is the projected visual angle of a target object and $\mathrm{d}\theta/\mathrm{d}t$ is the image expansion rate. This is local τ. Todd (1981) demonstrated that τ can be used by observers to discriminate the time-to-contact of an approaching object without access to absolute distance or velocity information about the object. Lee (1976) also proposed that $\dot{\tau}$ could work as a direct, informational controller for visually guided braking. $\dot{\tau}$ is simply the time derivative of τ. $\dot{\tau}$ specifies whether the level of deceleration or braking being used at any given moment is sufficient to stop at a given target location. Yilmaz and Warren (1995) tested whether participants would modulate a brake so as to maintain the value of $\dot{\tau}$ at or around a constant value of -0.5. Because $\dot{\tau}$ is the rate of change of τ and τ is equivalent to proportional change in the distance and velocity of a target, moving so as to maintain a constant $\dot{\tau}$ value produces specific deceleration trajectories that are determined by the initial distance and velocity of the moving observer. $\dot{\tau}$ values between -1.0 and -0.5 will require the observer to use braking that exponentially increases as the target grows very near, whereas values between -0.5 and 0 require the observer to brake strongly at first and then more and more gently as the target approaches, thereby greatly increasing the amount of time necessary to reach the target. In the case of values between -1 and -0.5, actors will find themselves at great risk for a crash if their braking capability cannot keep up with their braking requirements. Only maintaining a $\dot{\tau}$ value near -0.5 will bring the participants to a stop with soft contact at the target achieved by constant deceleration. Yilmaz and Warren (1995) found that $\dot{\tau}$ trajectories oscillated around the appropriate -0.5 margin value. However, Kaiser and Phatak (1993) argued that constant $\dot{\tau}$ does not entail information about the dynamics of braking and more specifically, does not specify what proportion of maximal braking capability must be used to null the error between the current and the ideal value of -0.5 (Fajen 2005). Accordingly, $\dot{\tau}$ does not provide information about when to initiate braking given one's braking capabilities (Fajen 2005). These problems undermined the constant $\dot{\tau}$ hypothesis and prompted researchers to explore a strategy based on the use of ideal deceleration.

The ideal deceleration strategy proposes that actors estimate the constant ideal deceleration needed to stop at a target location (Yates et al. 2004; Rock et al. 2006; Fajen 2005) Ideal deceleration is specified by the ratio of global optic flow (GOFR) to τ:

$$D_{\mathrm{i}} = v^2/2d = v/\tau = \mathrm{GOFR}/\tau$$

Here, v is current velocity and d is current target distance. The ideal deceleration strategy requires that τ must be used together with information about the actor's velocity.

Obviously, the assumption is that v = GOFR. As an actor moves toward an object, optical texture elements flow outward from the focus of expansion (FOE) at increasing rates given the distance of the texture elements from the FOE in the optic array. The magnitude of optic flow is a function both of optical position with respect to the FOE and of viewing distances to surfaces in the surrounding world. The average of the flow across the field (i.e., GOFR) is proportional to the observer's velocity as long as the average of the viewing distances to the surrounding surfaces does not change over time (Larish and Flach 1990). Fajen (2005) proposed an ideal braking strategy in which participants are required to brake so as to maintain deceleration between 0 and the maximum producible deceleration found through calibration of the brake.

Rock and Harris (2006) contrasted two τ-based control strategies (constant and ideal deceleration) in a real-world braking task and found that an ideal deceleration model produced the best fit to the data. The authors concluded that an ideal deceleration control strategy is more likely used in real-world task performance. However, the use of global flow information required by the ideal deceleration strategy is a problem in many braking tasks including those investigated in the current research.

Tasks in which a large surface looms to occupy an increasingly large area in the visual field violate the assumptions behind the use of GOFR and thus, cause the ideal deceleration theory to fail. Walking toward a door in a wall does not generate an optic flow pattern that is homogenous over time, so global flow information fails to specify observer velocity. The average distance to surrounding surfaces appearing in the visual field decreases as the wall is approached causing the global flow to accelerate. Circumstances typical to locomotion-to-reach tasks (e.g., walking to reach to a door knob or to reach for a dresser drawer handle or to shake someone's hand) and other braking tasks (e.g., driving up behind a truck at a stop light) render the use of the ideal deceleration strategy irrelevant. Performing locomotion-to-reach tasks in dark conditions (e.g., walking-to-reach to a lighted doorbell at night) also prevents the use of global flow and thus ideal deceleration. In the current experiments, we eliminated the presence of global flow to achieve better control of monocular and binocular τ-based information variables by having participants move to small, lit targets or point-light targets viewed in the dark.

Given the failings of both the constant $\dot{\tau}$ and ideal deceleration control strategies, Anderson and Bingham (2010) were inspired to hypothesize a new strategy, namely proportional rate control. The proportional rate control strategy requires participants to move so as to maintain a constant proportion between the rate of change of τ and τ itself, both shrinking as the actor approaches the target. A proportional rate control strategy requires only that actors perceive τ and be able to monitor its change over time. Choosing different proportional values will determine whether braking occurs faster or slower without incurring the deceleration debt that occurs when using a constant $\dot{\tau}$ strategy at values farther from zero than -0.5. This important feature means that error or variability in the selection of the ratio value or variation in brake performance will not necessarily lead to catastrophic failure as the actor approaches the target. Furthermore, before active control of approach is initiated, the proportion naturally evolves, eventually reaching a value chosen to be maintained as constant, at which active control is initiated.[1] The appropriate proportional value to be used can be calibrated to determine when to initiate the control of an approach. Anderson and Bingham (2010) found evidence that strongly supported the hypothesis that a proportional rate control strategy is used to guide targeted reaching visually.

Visually guided reaching

Visually guided reaching is well known to entail two forms of control: feedforward control and feedback control (e.g., Jeannerod 1990; Wing et al. 1996). While it is possible to perform reaches without online visual feedback, that is, in the dark after having seen the target, accuracy is limited and deteriorates rapidly with a delay of merely a few seconds (Hu et al. 1999). Some form of online feedback control is required for accurate reaches. Reaches performed with the target always visible but without the hand in view are more accurate (e.g., Bingham et al. 2007; Mon-Williams and Bingham 2007). Double step targeting studies have been performed in this way showing that inter-modal feedback control (involving vision of the target and kinesthetic perception of the hand) acts throughout a reach to yield more accurate performance (e.g., Prablanc and Martin 1992). Use of internal models of arm trajectories might also be involved, although Feldman has shown that elaborated mass-spring control organization may render the use of such internal models unnecessary (Feldman et al. 1990; Flanagan et al. 1993). Additional double step targeting studies (e.g., Bingham and Zaal 2004; Flanagan et al. 1993) as well as a variety of other studies (e.g., Anderson and Bingham 2010; Bingham 1995) have shown that visual feedback can be used once the hand is in view to yield accurate performance (for review, see Bingham 1995).

An outstanding question about the control of reach-to-grasp behavior, given this now well-established understanding of the organization, is what visual information is

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[1] Note that, before braking is initiated, $\dot{\tau}$ equals -1 so the proportion of τ to its rate of change is simply equal to $-\tau$. Thus, using the proportion to determine when to initiate braking is the same as just using τ to do it.

used for online guidance. Both binocular and monocular information can play a role in the feedforward control of reaching (e.g., Bingham et al. 2001; Mon-Williams and Dijkerman 1999). However, monocular information is not suitable for the guidance of the feedback portion of the reach (Bingham and Zaal 2004). Research suggests that binocular disparity matching can be used to achieve final contact of the hand at the target location (Bingham et al. 2001; Melmoth and Grant 2006). The question then would be: how are the dynamics of reaching controlled to achieve disparity matching?

Anderson and Bingham (2010) demonstrated that participants can visually guide targeted reaches using proportional rate control of relative disparity τ to achieve binocular disparity matching of the hand to the target. In this task, participants were required to sit at a table and reach in complete darkness to a point-light target under conditions of perturbed or normal inter-pupilary distance, that is, perturbed or normal perception of distance using vergence. When participants reached with an unseen hand, they mis-reached when distance perception was perturbed (and not otherwise). When a point light source was placed on a participant's index finger to make the hand visible, the participants now successfully guided their reaches to the targets despite perturbation of distance perception. Clearly, online visual guidance was used here to bring the hand to the target. Only binocular disparity-based sources of information were made available by the point-lights on target and hand. Finally, comparison of reaches performed with vision of the hand and with and without perturbation of distance perception showed that trajectories were the same in both cases. Furthermore, those trajectories revealed that participants used relative disparity τ to control the velocity of the hand as it moved toward the target.

Relative disparity τ is defined as:

$$\tau_\alpha = {}^{\alpha}\!\Big/{}^{\mathrm{d}\alpha}\!/\!{}_{\mathrm{d}t} = \frac{\Delta D}{V_\Delta}\left[1 - \frac{\Delta D}{D}\right],$$

where α is relative horizontal disparity ($\Phi_1 - \Phi_2$), $\mathrm{d}\alpha/\mathrm{d}t$ is rate of change of horizontal disparity, ΔD is the changing distance between hand and target, D is the distance between eye and target, and V_Δ is the velocity of the hand. (See Fig. 1.) (Note that this disparity τ measure is equal to monocular τ *with a perturbation*. The two are equal at limit when the target is reached, but not otherwise). Anderson and Bingham (2010) found that participants moved so as to maintain a constant proportion between the rate of change of disparity τ and disparity τ itself when all monocular sources of information were removed. The researchers then compared the performance of participants without monocular information with their performance in fully lighted conditions (with monocular information) and found no difference. This perceptual information strategy is important for the current work because it is a likely candidate to explain the control of the reaching component during a locomotion-to-reach task.

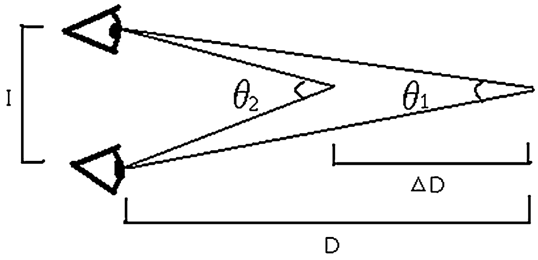

Fig. 1 Geometry of reaching to a target with binocular vision

Guiding locomotion-to-reach

Locomotion-to-reach is a nested action (or set of actions), and such actions have not received much attention. The challenge presented by such actions is one of coordination. How are the two nested actions coordinated with one another? In the case of locomotion-to-reach, both are visually controlled targeted actions and thus, both entail the use of visual information, and in particular, different forms of information. Eye-centric information can be used to guide locomotion as investigated in previous studies. If we assume τ-based control, then this information could be either monocular (e.g., Lee 1976) or binocular (e.g., Gray and Regan 1998, 2004; Regan and Gray 2004). Both monocular and binocular τ variables exist that can specify time-to-contact (TTC) with the eye, and these variables have been shown to be well used by human observers. Regan and Gray (2004) have shown that there are at least two different binocular τ variables that specify TTC with the eye. Because all these variables specify TTC with the eye, they are equivalent in this way and we will not distinguish among them, referring only to eye-centric τ variables used to control locomotion. However, as discussed by both Bingham and Zaal (2004) and Anderson and Bingham (2010), none of these variables can be used to control reaching because it requires the use of a hand-centric variable. Anderson and Bingham (2010) formulated relative disparity τ (a variable different from either binocular τ formulated by Gray and Regan) as a hand-centric information variable that specifies contact of the hand with a target, rather than the eye. Although this latter (or related) variables must be used to control reaching, they cannot generally be used to control locomotion if for no other reason than that the hand is generally not outstretched and in view during most of a locomotory approach. So, part of the coordination problem for this nested action is coordination of the alternative information variables that must be used to guide the different components of the action.

The presence and need for use of two different information variables creates a degrees-of-freedom (*df*) problem (e.g., Turvey et al. 1982). Generally, the human perception/action system handles the doing of two things at once by making them a single thing, that is, by coordination. In this case, we hypothesize that the coordination might be achieved by organizing the use of the two variables sequentially, that is, first eye-centric τ information is used to control locomotory approach and then, hand-centric τ information is used to control hand-centric approach. The remaining problem for this hypothesis is that control of locomotory approach likely continues during control of approach by the hand, and this circumstance would entail the detection and use of the two information variables at the same time, that is, still the *df* problem. However, if the reach is performed during the locomotory approach to achieve an outstretched arm and hand with the hand visible during the final phases of the approach, then the eye/head and hand would comprise a rigid body that could be controlled by controlling approach of the hand. This is a solution that would decrease the *df* as required and allow approach of both eye and hand to be controlled by the single relative disparity τ variable.

Under this hypothesis, two questions remain to be addressed as part of investigating the hypothesis itself. First, when and how is the switch accomplished between initial use of eye-centric information and final use of hand-centric information? Second, when and how is initiation of the reach accomplished? In this paper, we address the first of these questions and leave the second for a subsequent investigation. The way we approached this first question was to study the concurrent evolution of the two types of information, namely eye- and hand-centric τ variables. The two types of variables are not equivalent (as might be expected given that each cannot be used to control the task that requires the other), and thus, they follow different trajectories during the locomotion-to-reach approach. We investigated this using a special form of the locomotion-to-reach task, that is, participants locomoted to a target with their hand held outstretched and visible. That is, we asked participants to model the version of the *df* reduction strategy that we hypothesize for the control of the final approach of the hand to a target. The respective behavior of the two types of variables (eye and hand centric, respectively) in the context of the task as actually performed by our participants revealed how we should expect the two variables to be used and thus, when a switch from use of eye-centric and hand-centric information should be expected. This result will constrain the investigation of the second question in subsequent studies.

The current investigation initiates study of nested action as such, but there is an earlier study of locomotion-to-reach. Wann et al. (1993) studied whether holding $\dot{\tau}$ constant at -0.5 might be used to control deceleration of locomotion to stop with the eye (or nose) at a target and also to stop with the outstretched hand at a target. They did not investigate visual control of the reaching component. The study consisted of three experiments. The first compared adults running at speed and decelerating to a stop at a target. Wann et al. varied whether adults would stop with their outstretched hand or with their nose at the target location. The second experiment compared preschool children in the hand touch condition with adults in the same condition. The third experiment required either adult or preschool participants to perform a similar stopping task, but to touch the target with a baton. Wann et al. (1993) found that in the locomotion-to-reach tasks, the decelerations could be characterized as having two phases: a 'transport' phase and a 'homing' phase. The 'transport' phase was characterized by constant, linear deceleration, whereas the 'homing' phase was characterized by a sharper deceleration to a stop at the target.

To test the use of $\dot{\tau}$ strategies, Wann et al. (1993) fit both a one-slope and a two-slope linear regression to the momentary τ values generated during deceleration. For the locomotion-to-reach tasks, a two-slope regression fits the data better than a single-slope regression, reflecting the two-phase nature of the deceleration trajectories. These results showed that adult participants used a constant $\dot{\tau}$ at -0.5 strategy during the locomotion phase. The evidence from the work of both Yilmaz and Warren (1995) and Wann et al. (1993) supports the claim that constant $\dot{\tau}$ can be used by an observer to control his or her approach to stop at a target. However, Wann et al. (1993) found that a $\dot{\tau}$ strategy for a human observer locomoting-to-reach tended to break down when the observer was approaching reach distance. Logically, this would be indicative of a switch from the use of one to another of two distinct information variables.

If locomoting observers use a constant $\dot{\tau}$ control strategy for locomotory approach as found by Wann et al. (1993) and a proportional rate control strategy for reaching as found by Anderson and Bingham (2010), then during walk-to-reach, when participants switch to use relative disparity τ to control approach of the hand, they should also switch the control strategy to proportional rate control. Alternatively, it is possible that participants might use a proportional rate control strategy for *both* components of the nested task. Wann et al. evaluated the use of τ and $\dot{\tau}$ by using linear regression to estimate the rate of change of τ, that is, the $\dot{\tau}$ value during the controlled approach. Anderson and Bingham used the same analysis but analyzed the first and second halves of the trajectories (called 'split-half analysis') to discover whether the value of $\dot{\tau}$ was changing in a way consistent with proportional rate control. It was. $\dot{\tau}$ was near -1 early in the trajectory (i.e., τ was changing rapidly) and then dropped to near -0.25 late in the trajectory (i.e., τ was changing slowly). When Bingham and Anderson performed a single analysis on the entire trajectory, they obtained results like those of Wann et al., meaning that the average $\dot{\tau}$ value was -0.5. In the following experiment, we tested both simple locomotory approach to bring the eyes to a target and approach to bring the hand to a target. In each case, we performed split-half analyses to determine whether control reflected proportional rate or constant $\dot{\tau}$. We tested this for locomotion alone and then for locomotion with transition to hand control. We also tested the use of monocular as compared to binocular information.

Methods

Participants

Seven adult participants (four men and three women) aged 22–34 years participated in the experiment. Participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity measured using a Stereo Fly test (published by Stereo Optical Company, Inc.), and were naive to the purpose of the experiment. All participants were right-eye dominant and only one subject was left-handed. However, this subject reported no difficulty guiding the right hand to the target light during the hand-out case. All procedures were approved by and conform to the standards of the Indiana University Human Subjects Committee.

Procedure

Participants were required to perform two visually guided locomotion tasks under three viewing conditions. The two tasks were (1) moving the eyes to the target location and (2) moving the hand to the target location. In both tasks, randomly presented initial target distances were 7, 8, or 9 m from the participant. In Task 1, participants were required to jog to bring their eyes to a stop at a lighted target at eye height. Participants were instructed to come as close to the target as possible without touching it. In Task 2, participants were required to jog with their arm fully extended in front of their bodies during the entire trajectory while keeping their hand in a "thumbs up" position. (See Fig. 2.) Hand position was specified by a point light attached to the thumb. The goal was to bring the thumb to a stop immediately to the right of the target and thereby match the distance of the thumb and target in depth with respect to the eye. Participants were instructed not to occlude the target light while moving and always to move briskly. In both tasks, participants were told not to make corrections after coming to a stop at the target.

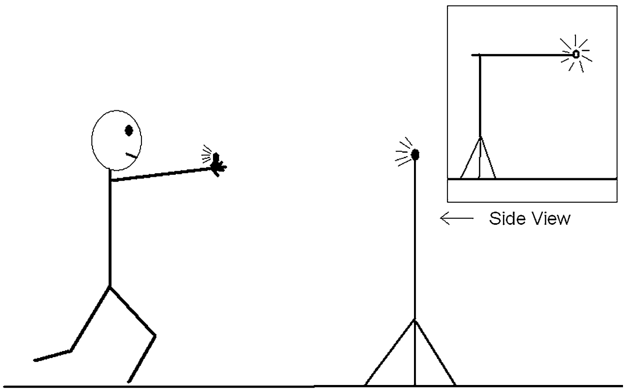

Fig. 2 Participants jogged with arm extended to bring their thumb to a stop just to the right of the target. Participants began moving between 7 and 9 m from the target and had no problems avoiding collision with either the target light or the target stand

In all cases, participants were moving in complete darkness with lights illuminating hand position, target position, or both as described. The target was specified either by a glowing sphere 5 cm in diameter (i.e., a target varying in image size as a function of distance and thus providing monocular information) or by a fiber-optic point light (i.e., a target with no image size variations and thus providing only binocular information). Participants were allowed either binocular vision or monocular vision achieved by placing an eye patch over the non-dominant eye (determined simply by asking participants). Combining these manipulations, participants completed the task under three viewing conditions:

- Monocular/Monocular (Mon/Mon)—Eye patch and glowing orb target
- Binocular/Monocular (Bin/Mon)—Full vision and glowing orb target
- Binocular/Binocular (Bin/Bin)—Full vision and a point-light target

In each of these viewing conditions and tasks, participants completed six movement trials such that two trials began from each of the three starting positions chosen at random. Each participant completed a total of 36 trials.

Data recording and analysis

3D motion data were acquired using an Optotrak infrared motion measurement system with markers that were not visible in the dark. A marker was placed on the rear of the post bearing the lighted targets to measure the spatial location of the target. Markers were also placed between and just above the participant's eyes, on the thumb pad facing the camera, and on the participant's right shoulder. Three-dimensional position data were recorded at 150 Hz. Motion data were transformed to a room-centered

Table 1 Mean and SD of endpoint accuracy for both head-to-target and hand-to-target conditions

Mean and (SD) endpoint accuracy	Mon/Mon	Bin/Mon	Bin/Bin
Head-to-target	+26.5 cm (20.4 cm)	+10.9 cm (6.3 cm)	+9.4 cm (6.3 cm)
Hand-to-target	+6.7 cm (13.6 cm)	+1.6 (2.7 cm)	+0.9 (3.8 cm)

The Mon/Mon viewing condition produced significantly less accurate results than both Bin/Mon and Bin/Bin in each case

coordinate frame of reference such that zero was the target position and participants moved along the *z* axis when moving toward the target. Only *z* position (motion-in-depth along the gaze axis) data were used during data processing because participants moved on a straight line trajectory along the gaze axis toward the target after coordinate transform. Entire movement trajectories were recorded, and both endpoint accuracy and the full movement trajectory along the *z* axis were used for analysis.

Raw data were recorded for each marker as 3D spatial coordinates defined as X (horizontal), Y (vertical), and Z (depth with respect to the eyes). The Optotrak camera was placed behind the target just below the ceiling at a 45° angle to the frontal parallel plane with respect to the participant and, therefore, raw data were coordinate-transformed (rotated around the *x* axis) to change the 3D coordinate space from camera-centered to room-centered coordinates. Data were recorded at 150 Hz beginning approximately 1 sec before the participant began moving and concluded approximately 1 sec after the participant verbally indicated that they had reached the target. The initiation and conclusion of data recording was controlled by the experimenter through a personal computer integrated with the Optotrak system.

All analysis on the raw data files was completed using a Matlab Version 7 program written by the authors. The program first transformed the raw 3D coordinate data as previously discussed, then filtered each XYZ-coordinate set for each target using two oppositely directed passes of a low-pass Butterworth filter with a resulting cutoff frequency of 7 Hz. Position, velocity, and acceleration change were then computed for each variable. The endpoint of a movement was said to have been reached when the participant's head or hand velocity drop below 1 cm/s.

Results

Eye-to-target

Endpoint accuracy

The participants' goal in this task was to move briskly to bring their eyes to the target location while taking great care never to come into contact with the target. Participants had no trouble completing this task and none ever collided with the target light. Given the task demands (do not hit the head on the target), it was reasonable to expect a small amount of undershooting. The relative amount participants undershot the target showed the degree to which participants could use the visual information to control their endpoint position. Participants completed this task under three viewing conditions: monocular viewing/target with image size (Mon/Mon), binocular viewing/target with image size (Bin/Mon), and binocular viewing/point-light target with no image size (Bin/Bin). The participants' goal was to move both quickly and accurately to the target. Participants' accuracy results showed high accuracy with the use of binocular vision and low (three times lower) accuracy with the use of monocular vision. Mean accuracy for Mon/Mon was 26.5 cm undershooting of the target with a comparable standard deviation of 20.4 cm, while mean accuracies for Bin/Mon and Bin/Bin were 10.9 and 9.4 cm undershooting, respectively, with standard deviations of 6.3 and 6.3 cm, respectively. (See Table 1.) A within-subjects ANOVA on accuracy with condition and trial as factors yielded a significant effect of condition ($F(2, 5) = 7.16$, $P < .01$). There were no other significant factors or interactions.

These endpoint accuracy results show that participants are less accurate when deprived of binocular information. This finding is understandable given previous results on the utility of vergence for making judgments about absolute distance (Mon-Williams and Dijkerman 1999). Although in theory participants could use image size information to control their endpoint accuracy, it is unlikely that this information would be useful here because participants were not given feedback about the actual target size. It is also apparent that participants were not able to use image size information reliably to control the endpoint as the variability in the endpoint position was also high relative to the binocular conditions. It is clear that monocular information alone is not sufficient to achieve accurate endpoint position. However, it is still possible that monocular τ-based information could be used to control the approach trajectory if not the accuracy of the endpoint.

Approach control

Previous research indicates that moving toward a target so as to maintain the rate of change of head centric τ (i.e., $\dot{\tau}$) around -0.5 will produce linear deceleration and bring actors to a stop at the target location with soft contact (Yilmaz and Warren 1995). Wann et al. (1993) demonstrated that running participants maintained constant $\dot{\tau}$ at -0.5 during deceleration toward a target. Given these findings, we expected that participants might maintain a constant $\dot{\tau}$ value around -0.5 during the approach of the head to the target-dot. To compute average $\dot{\tau}$ values across the participants, we first trimmed the movement trajectories for each trial by hand such that the beginning of each trajectory was the point of first deceleration after achieving peak head velocity. The end of each trajectory was the point at which τ reached the minimum before the characteristic exponential increase associated with stopping short of the target. We then computed the mean $\dot{\tau}$ value *within each trial for each trajectory*, using the formula for computing $\dot{\tau}$ from kinematic variables and averaging the resulting values across each trajectory. This analysis produced 42 $\dot{\tau}$ values for each task and condition. Such $\dot{\tau}$ values were then averaged across participants to provide a mean $\dot{\tau}$ value and a standard deviation *for each trial*. As a second measure, we computed $\dot{\tau}$ values associated with each trial by fitting a line by least squares regression to the trimmed τ trajectories. The slope of this line is equivalent to the rate of change of τ (i.e., $\dot{\tau}$). The r-square of this fit reflects the variability of $\dot{\tau}$. The two measures of $\dot{\tau}$ produced equivalent values. For further analyses, we used only the values produced by the linear regression fit method as that is the method used in the literature (Yilmaz and Warren 1995; Wann et al. 1993).

Mean $\dot{\tau}$ values for all conditions were near -0.5. Mean $\dot{\tau}$ values for Mon/Mon, Bin/Mon, and Bin/Bin were -0.50, -0.53, and -0.48, respectively. Mean r-square values for Mon/Mon, Bin/Mon, and Bin/Bin were 0.89, 0.94, and 0.90, respectively. A repeated-measures ANOVA with condition and trial as factors revealed no significant difference between these mean $\dot{\tau}$ values. These values are consistent with previous findings regarding the use of a constant $\dot{\tau}$ strategy for deceleration control (Yilmaz and Warren 1995; Wann et al. 1993).

We noted that mean $\dot{\tau}$ was also near -0.5 in Bin/Bin when no monocular information was present. This finding that participants must have used a binocular disparity-based $\dot{\tau}$ strategy involves one of the forms of binocular tau described by Gray and Regan (Gray and Regan 1998, 2004; Regan and Gray 2004). As we noted previously, using a constant $\dot{\tau}$ control strategy based on these binocular τ variables would produce movement trajectories indistinguishable from those predicted by a monocular $\dot{\tau}$ strategy and would, therefore, normally be impossible to distinguish post hoc. Another way to examine the potential differences in the use of information is through analysis of the variability between conditions. Participants produced the least variable trajectories when access to both monocular and binocular information was available. This provided some evidence that redundant sources of information about head centric τ may have improved the participants' ability to use a $\dot{\tau} = -0.5$ control strategy. Ultimately, due to the equivalence in world behavior, whether the approach control is based on monocular τ or binocular τ is of little consequence to the overarching purpose of this study. What is critical is merely that *some* τ-based information is used and then, to determine the nature of the control strategy.

These findings provide some support to previous claims that a -0.5 constant $\dot{\tau}$ strategy is used to control the approach of the head to a target. However, there is another possibility yet to be examined. As mentioned previously, participants may be moving so as to maintain a constant proportion between the rate of change of τ and τ itself. If participants are using this strategy instead of a constant $\dot{\tau}$ at -0.5 strategy, the resulting τ behavior would be such that both τ and $\dot{\tau}$ approach zero while the proportion between the two values remains constant as the participant approaches the target.

To examine this possibility, Anderson and Bingham (2010) employed a "split-half" analysis that was designed to compare $\dot{\tau}$ values during the first and second half of the approach trajectory as the participant approached the target. For the "split-half" analysis, we took each trimmed τ trajectory, found the median time sample in the trajectory, then split the trajectory into two components with the median time point at the end of the first component and the start of the second component. A linear regression analysis was then performed on each trajectory component to compute the slope (i.e., $\dot{\tau}$ values) for each half of the total movement trajectory. These halves were then compared to examine whether $\dot{\tau}$ values changed as the participant approached the target. If $\dot{\tau}$ values were changing in this way *and* the proportion values *did not* exhibit significant change between halves, then we could state that a proportional rate control strategy was being employed.

Results indicated a change in $\dot{\tau}$ during the Bin/Mon and Bin/Bin trials. A repeated-measures ANOVA on split-half values from Mon/Mon with trial and half as factors revealed no significant difference between the $\dot{\tau}$ values in each half ($P > .05$). A within-subjects ANOVA on split-half values from Bin/Mon with trial and half as factors yielded a significant difference between the $\dot{\tau}$ values in each half ($F(1, 6) = 24.29$, $P < .01$). The same analysis on split-half values from Bin/Bin yielded a significant difference between the $\dot{\tau}$ values in each half ($F(1, 6) = 13.5$, $P < .05$). Although it is unlikely that participants were using a constant proportion in the Mon/Mon case, these results indicated that they did use a proportional rate strategy when binocular information was available in the Bin/Mon and Bin/Bin cases. To complete the split-half analysis, we also performed this analysis on the proportional rate values (computed as the ratio between $\dot{\tau}$ and τ at each sample point) for each half and found no difference for either viewing condition. Within-subjects ANOVAs on split-half mean proportional rate values from Bin/Mon and from Bin/Bin with trial and half as factors yielded no significant difference between the proportional rate values in each half ($P > .05$). Mean proportional rate values for Bin/Mon and Bin/Bin were 0.77 and 0.70, respectively, with standard deviations of 0.08 and 0.09. These analyses reveal that both the Bin/Mon and Bin/Bin cases exhibited a control strategy based on maintaining a constant proportional rate between the rate of change of τ and τ itself. Interestingly, there is a significant difference between the mean proportional rate values for each half in the case of Mon/Mon. A within-subjects ANOVA on split-half ratio values from Mon/Mon with half and trial as factors yielded a significant difference between the proportional rate values in each half ($F(1, 6) = 17.08$, $P < .01$). The mean value for the half farthest from the target was 0.45 with a standard deviation of 0.08, while the mean ratio value for the half nearest to the target was 0.60 with a standard deviation of 0.07. This finding is consistent with a strategy based on maintaining a constant $\dot{\tau}$ because if $\dot{\tau}$ is constant, the ratio between $\dot{\tau}$ and τ will be changing. However, given the poor accuracy results, it could be equally likely that participants are simply moving more cautiously or erratically, so that their deceleration to a stop was abruptly controlled by another factor such as "image size is getting large, haul on the brakes." We expect that a strategy such as this would lead to less accurate end point control and larger endpoint standard deviations in stopping distance and that is exactly what we found.

The implications of using a proportional rate strategy are similar to those present in the case of visually guided targeted reaching by seated participants (Anderson and Bingham 2010). However, further discussion of this control strategy will be saved for a comparison of these data to simulated movement trajectories.

Locomotion-to-reach

Endpoint accuracy

The participants' goal in this task was to move briskly with their arm outstretched so as to match the distance of their outstretched hand to the distance of a target light at eye height and just to the right of the target. (Because there should have been no risk of collision with placement of the hand to the side of the target, we did not expect significant undershooting as we had in the eyes-to-target task.) Participants completed this task under the same three viewing conditions as in the eyes-to-target task. The goal was to move both quickly and accurately to the target. Results show high accuracy with the use of binocular vision and low accuracy (more than 4 times less accurate) with the use of monocular vision. Mean accuracy for the Mon/Mon condition was 6.9 cm undershooting of the target with a standard deviation of 13.2 cm, while mean accuracies for Bin/Mon and Bin/Bin were 1.6 and 0.9 cm undershooting, respectively, with standard deviations of 2.7 and 3.8 cm, respectively. A within-subjects ANOVA on accuracy with condition and trial as factors yielded a significant effect of condition ($F(2, 12) = 2.61$, $P < .01$). Mean accuracy results revealed a difference between accuracy in Mon/Mon when compared with both Bin/Mon and Bin/Bin. (See Table 1.) There were no other effects or interactions.

Results demonstrated that endpoint position in the monocular condition was highly imprecise in comparison with the binocular conditions. This finding was in line with the prediction that participants should use binocular disparity matching when binocular information is available. Clearly, there was no good monocular information available for accurate endpoint control and monocular information is not sufficient for placing the hand accurately at the target position. Results from the binocular conditions revealed good accuracy and showed the important role of binocular information for endpoint accuracy.

Control strategy: information switching

In previous research on a similar locomotion-to-reach task, Wann et al. (1993) found that participants used a constant $\dot{\tau}$ strategy during much of the approach, but then deviated from this approach trajectory during the reaching phase. Work by Anderson and Bingham (2010) uncovered a new proportional rate strategy involving the use of relative disparity τ for control of reaching. In light of these two findings, we expected that participants might switch from a τ-based information strategy for control of the head to a τ-based strategy for control of the hand. To investigate the presence of an information switch, we first computed τ for the head and relative disparity τ for the hand, each along the entire locomotory and reaching approach. For each trial, overlaying the hand disparity τ plot on the head τ plot revealed a consistent pattern across subjects and trials that can be seen in a representative trial in Fig. 3. The pattern is such that head τ began decreasing at a modest rate over the expected range. During this regime, hand disparity τ values were extremely large and outside of the range of useable values. These values were large because relative disparity τ is a measure of the time-to-contact of the two images of the hand with one another (assuming the observer is looking at the target). When an observer is far from the target but still approaching, the relative rate of change of relative disparity τ is small. Therefore, the time-to-contact value associated with the two images is large. As the participant

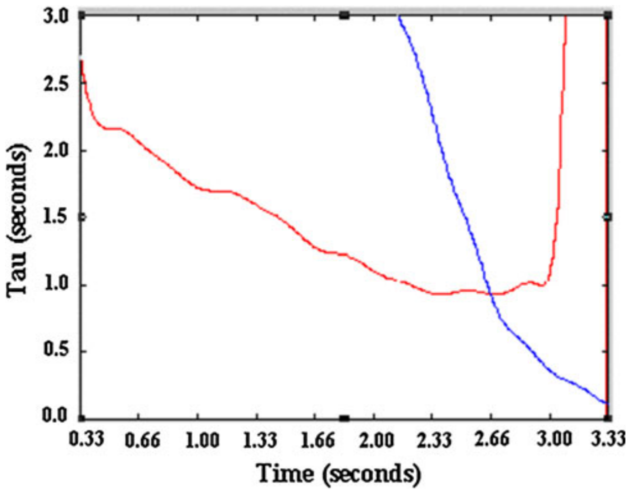

Fig. 3 Representative trial illustrating the transition from head τ information (early in time, *red*) to hand τ information (later in time, *blue*) as the participant approached the target. By hypothesis, switching from head τ information to hand τ information occurred when hand τ dropped below head τ. See text for further information

draws close to the target, both head τ and hand disparity τ values decrease. Finally, when the participant is two arm lengths from the target, the hand disparity τ values drop below head τ values and head τ values then begin to rise toward infinity. This behavior of head τ was expected given that the head, during reaching trials and as seen previously in the head only trials, will stop significantly short of the target. If the head stops short of the target, head τ never reaches zero and, on the contrary, increases exponentially. We expected that participants should use the smallest of alternative τ values to control approach, that is, the one signaling the closest proximity in time. The intuition is that one would always use the more conservative estimate of TTC. In the case of outstretched arm and hand, the hand τ value crossed the head τ trajectory to became the smaller of the two τ's at twice the arm length from the target. We hypothesized that this cross-point is the point at which actors would switch from the use of eye-centered control based on head τ to hand-centered control based on relative disparity τ.

Approach control: head

Based on the information switching results, further analyses treat the head control and the hand control as separate entities that are coupled by the particular demands of this task. As mentioned previously, we hypothesized that participants switch from control of the head to control of the hand as hand τ falls below head τ. During the initial locomotory phase of motion, hand τ information is changing purely as a function of head/body motion controlled by head τ information. Therefore, we first analyzed the control strategy governing the motion of the head as the participant approached the target.

Given the findings in the eyes-to-target condition, we expected that participants should exhibit, on average, a constant $\dot{\tau}$ value of about -0.5 during the approach of the head to the target. To compute average $\dot{\tau}$ values across the participants, we first trimmed the movement trajectories for each trial by hand such that the beginning of each trajectory was the point of first deceleration after achieving peak head velocity and the end of each trajectory was the point at which hand τ dropped below head τ (the switch point). We then computed the $\dot{\tau}$ value *within each trial for each trajectory* using the same linear regression technique as in Task 1. These $\dot{\tau}$ values were then averaged to provide a mean $\dot{\tau}$ value and a standard deviation *for each trial* in each condition. A within-subjects ANOVA with condition and trial as factors yielded no significant difference between these mean $\dot{\tau}$ values ($P > .5$). All values were near -0.5 consistent with previous findings. Mean $\dot{\tau}$ values for Mon/Mon, Bin/Mon, and Bin/Bin were -0.50, -0.53, and -0.48, respectively. Mean r-square values for Mon/Mon, Bin/Mon, and Bin/Bin were 0.89, 0.94, and 0.90, respectively.

As in the previous locomotion-only condition, mean $\dot{\tau}$ was -0.5 in the Bin/Bin condition when no monocular information was available. Again, this must have reflected the use of eye-centric binocular $\dot{\tau}$. We compared the use of monocular versus binocular $\dot{\tau}$ through analysis of the variability between conditions. As expected, comparison of the mean within trial variability of $\dot{\tau}$ across conditions using a repeated-measures ANOVA with condition and trial as factors yielded a significant difference between mean $\dot{\tau}$ standard deviations over conditions. As in the previous case, participants were the least variable when access to both monocular and binocular information was available. It seems apparent that redundant sources of information about head τ improved the participants' ability to use a $\dot{\tau} = -0.5$ control strategy. On the other hand, this could only be true if, in fact, that was the control strategy being employed.

Although these results provide support for the hypothesis that participants used a control strategy based on constant $\dot{\tau}$ equal to -0.5, we expected that these results would in fact be a by-product of a constant proportional rate control strategy and a single linear fit over the entire locomotory approach trajectory. Next, using the split-half analysis previously introduced, we examined whether the $\dot{\tau}$ values changed systematically across the trajectory. We found that, in all three viewing conditions, $\dot{\tau}$ values changed systematically over the trajectory to approach zero as the participant approached the target. A repeated-measures ANOVA with condition, trial, and half as factors yielded a significant difference between halves but no difference between conditions or trials ($F(1, 6) = 14.72$, $P < .01$). There were no significant interactions. Mean slopes for each half for Mon/Mon, Bin/Mon, and Bin/Bin were −0.57, −0.62, and −0.67 for the half far from the target and −0.49, −0.42, and −0.31 for the half near to the target. These results indicated that participants used a proportional rate control strategy, not a constant $\dot{\tau}$ strategy, to guide the head to the target during the locomotory component of the trajectory.

Performing the split-half repeated-measures ANOVA (with condition, trial, and half as factors) on the $\dot{\tau}/\tau$ proportional rate values for the head yielded no significant differences or interactions ($P > .05$). Overall mean ratio values for these viewing conditions were 0.52 (0.09), 0.62 (0.06), and 0.59 (0.06), respectively. These results support the claim that participants were using a constant proportional rate strategy, not a constant $\dot{\tau}$ strategy, to guide their head motion and doing so in all three conditions. Participants were moving so as to maintain a constant proportional rate of change of τ relative to τ itself at proportion values between 0.5 and 0.6.

Approach control: hand

As the participant drew near the target, the switch from control based on head τ to control based on hand disparity τ appeared to take place. Based on findings by Anderson and Bingham (2010), we hypothesized that participants would move so as to maintain a constant proportion between the rate of change of relative disparity τ and relative disparity τ itself to guide the hand portion of the movement trajectory to the target. To examine this hypothesis, we performed the split-half analysis. However, as discussed in the introduction, there was no need to pit a strategy based on a constant $\dot{\tau}$ against a strategy based on proportional rate. Anderson and Bingham (2010) demonstrated that reaching is robustly controlled using a proportional rate strategy based on relative disparity τ. The viewing conditions in that task were nearly identical to those in the current experiment. Also, there was no need to analyze the strictly monocular viewing condition because the endpoint accuracy results indicated that participants were significantly less accurate when required to use only monocular information and could not accurately guide the hand to the target. Bingham and Zaal (2004) showed why monocular information would be unusable in guiding the hand because the information is eye centric. In light of all this, we only performed a split-half analysis on the $\dot{\tau}/\tau$ ratio values from Bin/Mon and Bin/Bin to examine whether the proportional rates changed or remained constant during the hand-control portion of the trajectory.

To compute average $\dot{\tau}/\tau$ ratio values across the participants, we first trimmed the movement trajectories for each trial such that the beginning of each trajectory was the point at which relative disparity τ (hand τ) values dropped below head τ values (the switch point). The end of each trajectory was the point at which hand τ either moved past zero (indicating that the participant crossed the plane of the target) or the minimum in disparity τ before the disparity τ trajectory began to rise exponentially (indicating that the participant stopped short of the target). We then computed the proportional rate value *for each trial* by taking the mean of all sample values over the trajectory excluding the top and bottom five percent. This trimming was not strictly required for most trials but served to eliminate occasional outliers naturally produced when computing derivatives of human movement data. These proportional rate values were then averaged to provide a mean proportional rate value and a standard deviation of the values *for each trial* in each condition. We then performed a split-half analysis on these means that yielded no difference between halves. A repeated-measures ANOVA performed on trial means with condition, trial, and half as factors yielded no significant difference between these overall mean proportional rate values ($P > .05$).

Simulated trajectories

To test the information switching model, we generated simulated movement trajectories and used them to predict changes in both head τ and hand τ given initial conditions taken from the data. We performed this analysis in two different ways. First, for each trial, we created a corresponding simulated trial using initial conditions taken from the corresponding trial's initial conditions. Second, we created simulated trials using initial conditions from mean values across all trials. To simulate a switching strategy, we simulated movement trajectories for the case of an observer moving toward a target with their hand extended. Our simulations worked such that the movement trajectory was prescribed by control based on head τ information initially and then hand τ information later in the trajectory. When the head was the driver, hand τ control was turned off (thus here hand τ changed only as a function of head motion). When the hand was the driver, head τ control was turned off (thus here head τ changed only as a function of hand motion). The transition between head and hand control occurred when hand τ dropped below head τ. Model initial conditions in all cases were initial velocity, constant head-to-hand distance (arm length), initial head distance, and the constant $\dot{\tau}$ and/or constant proportional rate values depending on the condition. We ran simulations using values for the constant $\dot{\tau}$ and/or constant proportional rate determined in one of two ways. First, values determined from the data for each trial were used to simulate that trial, respectively. Second, means computed across the trials within a condition were used.

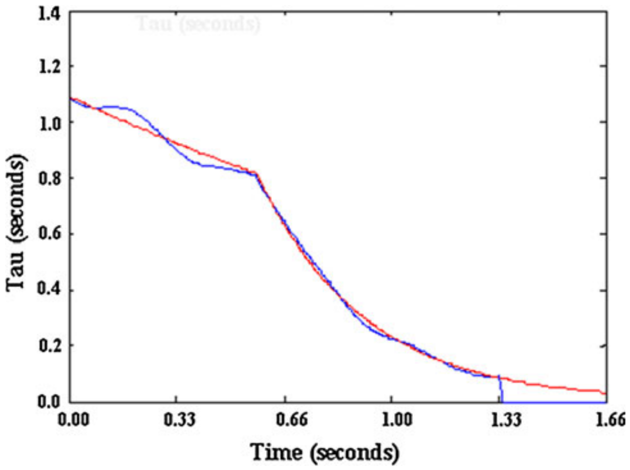

Fig. 4 Representative trial showing simulated, combined head and hand τ vector (*red*) plotted on top of the corresponding actual combined head and hand τ vector (*blue*) plotted against time in seconds. The simulated vector plotted here uses initial constants taken from the trial represented by the actual data vector plotted here

Using Simulink in Matlab Version 7, we modeled the task in two ways. First, we used a constant monocular $\dot{\tau}$ strategy for control of head motion and a proportional rate disparity τ control strategy for the hand motion. Second, we used a proportional rate monocular τ strategy for the control of head motion and a proportional rate disparity τ strategy for hand motion.

For model case one, two simulated τ vectors for each trial were produced by the simulations: monocular head τ and disparity hand τ. These two vectors were combined by joining the head τ trajectory from the start of the simulation until the point at which disparity hand τ dropped below monocular head τ (the cross-point) to hand τ from the point at which disparity hand τ drop below monocular head τ (the cross-point) to target acquisition. The combination of these two vectors produced a τ vector corresponding to the simulated movement of a participant in each trial with initial values taken from either the Bin/Mon case or the Bin/Bin case. These vectors were then correlated with vectors produced using the same method from the actual data. If participants used a control strategy based on switching from head-τ control to hand-τ control *and* used a constant monocular head $\dot{\tau}$ control strategy combined with a constant disparity hand τ ratio strategy, then we expected a high correlation between combined τ vectors for each trial when correlated with combined τ vectors for each corresponding simulated trial (see Fig. 4 for a representative trial).

When performing simulations using trial-by-trial constants for a constant $\dot{\tau}$ control strategy for the head and a proportional rate control strategy for the hand, we found mean $r^2 = .89$ and mean $r^2 = .89$ for Bin/Mon and Bin/Bin, respectively. When simulating the same conditions using mean values for the constants (as reported above), we found mean $r^2 = .85$ and mean $r^2 = .91$ for Bin/Mon and Bin/Bin, respectively.

When simulating using trial-by-trial constants for a proportional rate control strategy for the head and for the hand, we found mean $r^2 = .89$ and mean $r^2 = .90$ for Bin/Mon and Bin/Bin, respectively. When simulating the same conditions using mean values for the constants, we found mean $r^2 = .87$ and mean $r^2 = .91$ for Bin/Mon and Bin/Bin, respectively. In short, the simulations fit the data very well, but they did not allow us to discriminate between the two possible head control strategies. However, the results of the previous split-half analyses indicated that the locomotory approach was controlled using the same strategy as used to control the reaching, namely proportional rate control.

Discussion

In this work, we explored the task of locomoting-to-reach by investigating the perceptual information and strategy used to control the action. Results indicated that participants rely on τ-based information for the control of both the locomotion phase and the reaching phase of the movement. Results also indicated that participants switch from head-centered control to hand-centered control as they draw near to the target. During head-centered control, participants move so as to maintain a constant proportion between the rate of change of τ and τ itself, where τ is defined relative to the eye using either monocular or binocular versions (or both). In this regime, hand τ (relative disparity τ) was decreasing steeply as a function of motion guided with respect to the head. At the moment hand τ fell below the value of head τ, participants switched from controlling the motion of the body with respect to the head to controlling it with respect to the hand by maintaining a constant proportion between the rate of change of relative disparity τ and relative disparity τ itself. This switching strategy is advantageous because it allows actors to rely on only one optical variable at a time during approach and it requires no information other than that specified by τ variables and thus the use of a single control strategy with sequential use of the two different τ variables.

Although we found through modeling some evidence that participants could use a constant $\dot{\tau}$ strategy instead of a proportional rate strategy for control with respect to the head, the evidence from analysis of the data indicated that the proportional rate strategy is the control strategy that participants actually use when completing the task. The proportional rate strategy is the more parsimonious explanation for the control of the head in that it does not require participants to switch the *strategy* for the use of τ-based information. In other words, it is clear that participants use a proportional rate strategy for the control of the hand-centered component of the movement. If participants use a proportional rate strategy for the control of the hand-centered portion, then it seems reasonable to believe that they would also use this strategy for the control of head-centered motion if it is available. We found that it is both available and used. Also, there are a number of important studies calling into question the use of monocular $\dot{\tau}$ as a control variable for braking (Fajen 2005). These experiments hypothesized and demonstrated good evidence that participants may use the ideal deceleration strategy mentioned previously to control braking. However, this strategy would not be appropriate for common locomoting-to-reach tasks such as walking to open a door. The ideal deceleration strategy relies on global flow information to specify locomotion velocity. In our experimental task, global flow information was not present as the room was completely dark. In the more general case, locomoting-to-reach tasks often take place in spaces where global flow information may be biased by, for instance, walking toward a wall with a door. Velocity from global flow would be distorted in these approach conditions. Therefore, using a strategy based on local τ information such as a proportional rate strategy would be an advantageous and appropriate solution.

There are also a number of other advantages to using a proportional rate strategy for control. A proportional rate strategy is not rigid with respect to time in the way a constant $\dot{\tau}$ approach is rigid. Using a proportional rate strategy allows the actor to choose different proportional rate values to control the rate of deceleration once calibrated to the brake (or more generally, to the capability for deceleration). Constant $\dot{\tau}$ at -0.5 is rigid and prescribes a constant deceleration and, therefore, rigid timing with respect to stopping at a target location. However, if an actor happens to not be perfectly calibrated to their capability for deceleration, then a proportional rate strategy is even more important because it allows a window in which deceleration can be successful even if a ratio value initially chosen by the actor is too low. In other words, a proportional rate τ-based approach can be "ball-parked" because a proportional rate strategy is not as sensitive to variability as a constant $\dot{\tau}$ strategy. The proportional rate strategy is more stable.

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