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RESEARCH ARTICLE

# A solution to the online guidance problem for targeted reaches: proportional rate control using relative disparity $\tau$

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**Abstract** We provide a solution to a major problem in visually guided reaching. Research has shown that binocular vision plays an important role in the online visual guidance of reaching, but the visual information and strategy used to guide a reach remains unknown. We propose a new theory of visual guidance of reaching including a new information variable, $\tau_\alpha$ (relative disparity $\tau$), and a novel control strategy that allows actors to guide their reach trajectories visually by maintaining a constant proportion between $\tau_\alpha$ and its rate of change. The dynamical model couples the information to the reaching movement to generate trajectories characteristic of human reaching. We tested the theory in two experiments in which participants reached under conditions of darkness to guide a visible point either on a sliding apparatus or on their finger to a point-light target in depth. Slider apparatus controlled for a simple mapping from visual to proprioceptive space. When reaching with their finger, participants were forced, by perturbation of visual information used for feedforward control, to use online control with only binocular disparity-based information for guidance. Statistical analyses of trajectories strongly supported the theory. Simulations of the model were compared statistically to actual reaching trajectories. The results supported the theory, showing that $\tau_\alpha$ provides a source of information for the control of visually guided reaching and that participants use this information in a proportional rate control strategy.

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## Introduction

Reaching under visual guidance to touch or grasp a target object is well known to entail both feedforward and online feedback control (Jeannerod 1990; Wing et al. 1996; Shadmehr and Wise 2005). Visual space perception yields information used to guide the initial feedforward portion of a reach. Both monocular and binocular information can specify the distance, direction, size and shape of a target object (e.g. Bradshaw et al. 2004; Bingham et al. 2001; Jackson et al. 1997). However, that information is neither accurate nor precise enough for targeted reaches to be reliably fast and accurate if performed only under feedforward control (Bingham et al. 2000, 2001; Bingham and Pagano 1998; Tittle et al. 1995; Todd et al. 1995). Calibration of such information using feedback from the terminal portion of successive reaches improves feedforward control (Bingham et al. 2007; Coates et al. 2008; Mon-Williams and Bingham 2007) and, especially with calibration, binocular information about target distance has been found as expected to yield more rapid and accurate feedforward reaching than does monocular information (Bradshaw and Elliott 2003; Bradshaw et al. 2004; Servos et al. 1992). Nevertheless, the need remains for online visual feedback to guide the hand and fingers through to final contact with a target object if that contact is to be achieved rapidly and smoothly without colliding with the target (Lee et al. 2008; Servos and Goodale 1994). The problem is not just to bring the hand and fingers to the position of the relevant object surfaces but also that the velocity of the hand has to be controlled so that it is near zero when contact

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is finally achieved. This is the dual challenge for visual online guidance of reaching, to control both spatial and dynamic aspects of the targeted reach.

We present a new theory of the visual online control of reaching that meets this dual challenge by allowing flexible control of the timing of movement to bring the hand to a stop at the position of a target object. A theory of visual guidance of reaching requires both a visual information variable and a control strategy or dynamic in which that variable is used to bring the hand to a target. We describe a new information variable, relative disparity $\tau$, and a new strategy for using this variable to guide a reach. The specific advantage of the new control dynamic is that it allows timing flexibility that, at the same time, yields good stability of the behavior. This strategy, called 'proportional rate control', requires the actor to move so as to maintain a constant proportion between relative disparity $\tau$ and its rate of change. We first review past work on control of approach behaviors and online guidance of reaching. Then, we develop and present the dynamical model for control of reaching. Next, we test the model in two experiments. The first experiment tested whether participants could use disparity matching to guide reaches while controlling for direct mapping from visual to proprioceptive space. The second experiment tested online guidance of reaches under conditions that isolated the relevant stereo information and perturbed information that could be used in feedforward control. The resulting trajectories were analyzed and compared to trajectories predicted by the theory. The results supported the new theory.

## Previous research on control of approach behaviors

In the past, the dual challenge for the control of approach has been addressed in the context of locomotory approach behavior, that is, the control of breaking in automobile driving when approaching a stop or the control of approach by a running observer. These behaviors involve the control of approach of the entire body, and in particular, of the head and eyes to a target location. Lee (1976) proposed both an information variable (namely, monocular $\dot{\tau}$) and a control strategy that could be used to achieve 'soft contact', that is, velocity equal zero just as target position is achieved. The control strategy was to move so as to maintain monocular $\dot{\tau}$ at a value of $-0.5$.

Monocular $\tau$ can be described as the ratio of image size to image expansion rate. It specifies time-to-contact when a moving object approaches the observer at constant velocity. Todd (1981) showed that human observers are exceptionally sensitive to differential values of monocular $\tau$. Regan and Hamstra (1993) showed that differential thresholds to monocular tau were less than those for image expansion rate and thus, that monocular $\tau$ is a variable measured and detected as such by the visual system, independent of the detection of image expansion rate. $\dot{\tau}$ is the temporal rate of change of monocular tau, that is, its time derivative. Controlling one's locomotory approach to a target so as to hold monocular $\dot{\tau}$ at a value of $-0.5$ yields constant deceleration to a stop right at the target. $\dot{\tau}$ values between $-1.0$ and $-0.5$ require the observer to use near-infinite braking as the target grows very near whereas values between $-0.5$ and 0 require the observer to brake more early as the target approaches thereby greatly increasing the amount of time necessary to reach the target. Only maintaining a $\dot{\tau}$ value near $-0.5$ will bring the participant to a stop with soft contact at the target *and* with constant deceleration. Both Yilmaz and Warren (1995) and Wann et al. (1993) found that locomotory approach behaviors, control of automobile-like braking and of the approach of a runner to hand-off a baton, respectively, exhibited constant $\dot{\tau}$ control maintaining $\dot{\tau}$ at $-0.5$. The great advantage of this information and control strategy is that it simultaneously solves the dual spatial and dynamic control problems of approach behaviors.

## Previous research and online control of reaching

Unfortunately, as shown by Bingham and Zaal (2004), monocular $\dot{\tau}$ cannot be used to control the approach of one's hand to a target object in reaching. Bootsma and Peper (1992) formulated a way that such monocular variables might be used to guide reaches, but the analysis required that the hand does not deviate from a straight path. Bingham and Zaal (2004) pointed out that the online adjustments of a targeted reach would characteristically entail departure from such a straight path because of the very shortcomings of space perception for which the control strategy was required to compensate. Accurate perception of the distance of a target is required if the hand is to travel a straight path to that target from some arbitrary initial position. Visual distance perception is simply not sufficiently accurate for this and is part of the reason online guidance of a reach is required. Monocular $\tau$-based information cannot be used to guide a reach to the distance of a target from the observer. Aside from this, other kinds of monocular information might still be of use in guiding targeted reaches in the case when the hand travels over an extended background surface that supports the targeted object, that is, for instance, reaching across the dinner table for the salt. However, reaches are perhaps more often targeted to surfaces with no intervening underlying visible support surface. For instance, reaching to the back of one's dinner chair to pull it away from the table to be seated. Other examples are reaching to a door knob, to open a kitchen cabinet, to the faucet of the kitchen sink, to the handle of a pan on the stove, to open the oven, to flip a wall switch for a light, and on and on for countless targeted reaching tasks. How might such reaches be visually guided for soft contact at their targeted locations?

Binocular vision has long been assumed to be of particular use for the control of reaching and grasping (Marzke 1994), but recent studies reveal that its primary relevance to reaching is for online feedback control of the decelerative portion of a reach (Bradshaw and Elliott 2003; Bradshaw et al. 2004; Jackson et al. 1997; Melmoth and Grant 2006; Servos and Goodale 1994; Servos et al. 1992). Binocular vision is uniquely suited for positioning the hand at a target through disparity matching (Melmoth and Grant 2006), that is, by moving to eliminate the relative difference in disparity of the hand and target. Characteristically in visually guided reaching, one looks at the target of a reach. In this case, the two eyes both verge on the target and the approaching hand appears to have two disparate images. As the hand approaches the depth plane of the target, the two images approach one another and join into a single image as the hand contacts the target.

Results from a task requiring participants in a virtual environment to move a stylus to touch a 3D target demonstrate that individuals can use disparity matching to guide accurate reaches (Bingham et al. 2001). In this task, participants viewed a virtual target object and a virtual stylus that represented their hand. They were asked to reach with the stylus to touch the object. The virtual object and stylus were controlled such that the stylus could never be occluded by the object even when it passed the distance of the object and traveled along the same visual direction (i.e. normally it should have been occluded when passing through the object). This control eliminated the ability of participants to use occlusion of the stylus by the object as a cue for the termination of the reach. Obviously, they also could not use physical contact to do this either. When participants used monocular vision to do the task, they failed entirely to place the stylus at the object. When they used binocular vision, they performed accurately thus supporting the notion that individuals can use relative disparity matching to guide reaching.

So, disparity matching can be used to solve the spatial control problem in reaching, but how is the dynamic control problem to be solved? How is deceleration of the hand controlled to achieve soft contact at the target? $\tau$-type variables can be used to achieve this kind of control, but monocular $\dot{\tau}$ can only be used to control approach of the eye and head to a target. A new theory adapts $\tau$-based control to the control of reaching by applying the visual control to the approach of the two disparate images in disparity matching.

According to this theory, the information used to guide a reach is relative disparity $\tau$. This $\tau$ is new and different from monocular $\tau$. Monocular $\tau$ corresponds to the ratio of distance and velocity of the moving objects in the world, and thus, in the case of approach at constant velocity, monocular $\tau$ specifies Time-To-Contact (TTC). Relative disparity $\tau$ corresponds to the ratio of optical distance and optical velocity of two disparate images in stereo vision and thus, could only directly specify the TTC of the two images. The relation of TTC defined by relative disparity $\tau$ to the TTC of the hand and target object in the world is perturbed. Gray and Regan (1998) noted this difference and proposed a different binocular optical $\tau$ variable that does specify TTC in the world. However, that variable, absolute disparity $\tau$, is about contact of the eye with a target just as is monocular $\tau$. In fact, the two are equivalent because they are equal to the ratio of distance of the eye from a target to the velocity of the approach. Neither binocular $\tau$ as defined by Gray and Regan (1998) nor monocular $\tau$ can be used to guide reaching.

## A new information variable for the online control of reaching

We now define a new relative disparity $\tau_\alpha$ that can be used to guide reaching. Figure 1 shows the space of the observer's eyes separated by some interpupilary distance ($I$) and the disparities of the observed hand ($\Phi_2$) and the target ($\Phi_1$). $\tau_\alpha$ is defined as:

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

where $\alpha$ is relative horizontal disparity ($\Phi_1 - \Phi_2$), d$\alpha$/d$t$ is rate of change of horizontal disparity, $\Delta D(=\Delta D(t))$ is the changing distance between hand and target, $D$ (a constant) is the distance between eye and target, and $V_\Delta$ ($=V_\Delta$ ($t$)) is the velocity of the hand (the rate of change of $\Delta D$). Notice that the bracketed portion of the equation perturbs the value of $\tau_\alpha$ from the actual TTC of the hand and target in the world and that $\tau_\alpha$ converges on TTC as $\Delta D/D$ goes to zero.

To control the deceleration of the hand as it moves away from the observer and toward the target, a continuous $\dot{\tau}$ measure based on relative binocular disparity could be used.

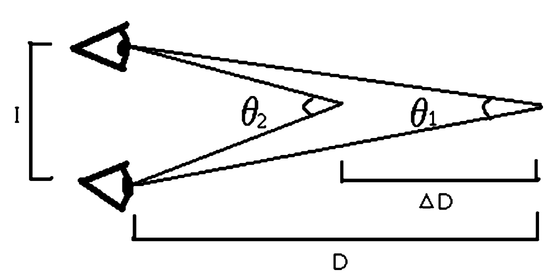


**Fig. 1** Geometry of reaching to a target with binocular vision. See the text for explanation

Disparity $\dot{\tau}_\alpha$ is defined as:

$$\dot{\tau}_\alpha = 1 - \frac{A_\Delta}{V_\Delta}\tau_\alpha - \frac{2\Delta D}{D}, \quad (2)$$

where $\Delta D$ is the changing distance between hand and target, $D$ is the distance between eye and target, $V_\Delta$ is the hand velocity, and $A_\Delta$ is the hand acceleration. $\dot{\tau}_\alpha$ is a possible source of information for the visual guidance of reaching to a target under conditions of binocular vision. Again, note that the $\dot{\tau}_\alpha$ value is perturbed from actual world $\dot{\tau}$ values by the third term in the equation.

## A new control strategy for the online control of reaching and simulations thereof

We have proposed a new information variable, $\dot{\tau}_\alpha$, that could be used for the online guidance of reaching. In what control strategy might it be used? The strategy originally suggested by Lee (1976) would be to move the hand so that $\dot{\tau}_\alpha$ remains at a constant value until the target is acquired. We will refer to this strategy as the 'constant $\dot{\tau}_\alpha$' strategy. A second strategy for visually guiding reaching would be to move so as to maintain a constant proportion between $\tau_\alpha$ and its rate of change. We will refer to this strategy as the 'proportional rate control' strategy. The advantage of this second strategy is that it allows flexible control of timing and this, in turn, yields greater stability.

Effectively, $\dot{\tau}_\alpha$ controls the time it will take for the hand to reach the target. If $\tau_\alpha$ is time until the target is acquired, then $\dot{\tau}_\alpha$ determines how quickly that time is diminished. A constant $\dot{\tau}_\alpha$ strategy places rigid limits on the timing of a movement so that the movement time is strictly defined by the movement (its distance and velocity) at the initiation of braking. However, it is possible to manipulate the timing of a reach by manipulating $\dot{\tau}_\alpha$ *during* the course of a reach. For example, change of the $\dot{\tau}$ value from around $-1$ to around $-0.2$ during an approach would produce fast movement during the initial phase of approach and slow movement at the end of the approach without incurring the deceleration debt and exponential braking required in constant $\dot{\tau}$ approaches with values less than $-0.5$ (i.e. $-1$). The problem is that this strategy, by itself, introduces a regressive demand for additional information, namely, information about how to time the changes in $\dot{\tau}$. This problem is solved by proportional rate control. Simply move so as to keep the rate of change of $\tau$ in constant proportion to $\tau$ itself. Both decrease over time so the result is large initial $\dot{\tau}$ and subsequent small $\dot{\tau}$. The proportional rate constant can be selected to determine the timing of the movement. In addition, a proportional rate strategy is stable in the face of perturbations to the system such that a window of proportional rate values will yield successful braking without a crash. For example, if an actor's braking capability decreases during a movement, it does not necessarily lead to a crash since the actor can increase the proportional rate control value without necessarily incurring deceleration debt as would be the case if the actor was using a constant $\dot{\tau}$ strategy (see Marks et al. (in preparation) for dynamical analyses demonstrating these properties of this control strategy.) To illustrate control strategies using $\tau_\alpha$, we simulated reaching trajectories using both a constant $\dot{\tau}_\alpha$ and a $\tau_\alpha$ proportional rate control strategy.

In the following simulations, we generated predicted reach trajectories given representative initial conditions by integrating the equations for $\dot{\tau}_\alpha$ over time. All simulations were performed using SimuLink (MATLAB v7). To integrate these equations, we first transformed the $\dot{\tau}_\alpha$ equation to isolate acceleration. We then input initial conditions for eye position, hand position, velocity, and either a constant $\dot{\tau}_\alpha$ value or a proportional rate value, that is, $\dot{\tau}_\alpha = k * \tau_\alpha$, for some value of $k$, the proportional rate constant. When determining initial conditions, we used data from representative, successful reaching trials selected by the experimenter.

First, we performed simulations of a constant $\dot{\tau}_\alpha$ control strategy using an initial eye-to-target distance ($D$) of 50 cm, an initial hand-to-target distance of 35 cm ($\Delta D$), and an initial hand velocity of $-35$ cm/s. These values are representative of values occurring slightly before peak velocity of the hand. Under these conditions, the simulated hand contacted the target after just over half a second of movement time. This movement time is relatively close to actual times for movement from peak velocity to reach termination. As seen in Fig. 2a, the model predicted a rapid change in hand-target distance until moments before target contact when change slowed slightly. Unfortunately, the deceleration required to produce this trajectory was well above what is normally produced in human reaching. Indeed, the deceleration predicted by the model never actually returned to zero as would be expected in the case of controlled reaching. When deceleration grows to unrealistic values before the target is acquired, this implies that a crash would have occurred. This simulation indicated that a constant $\dot{\tau}_\alpha$ strategy with $\dot{\tau}_\alpha$ at $-0.5$ is not suitable for controlling human reaching.

Using the same initial conditions, we next simulated an approach with $\dot{\tau}_\alpha$ held constant at $-0.3$. As can be seen in Fig. 2b, this produced somewhat similar trajectories except that the acceleration values went to zero at target contact and were within a more realistic range for human reaching. Thus, it appeared that a constant $\dot{\tau}_\alpha$ strategy could be a potential candidate for a successful control strategy using a value for constant $\dot{\tau}_\alpha$ in the neighborhood of $-0.3$.

Next, we simulated a proportional rate control strategy using the same initial conditions as in the previous

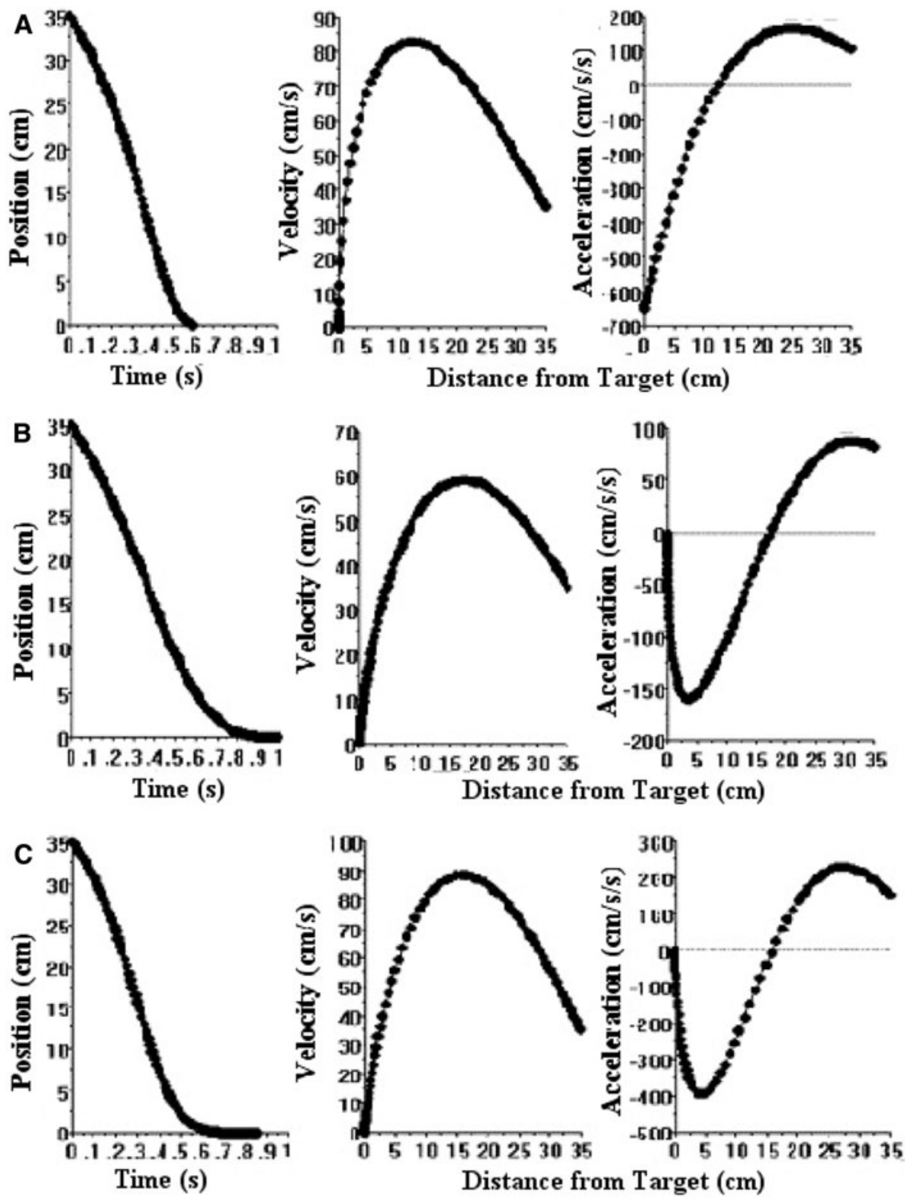


**Fig. 2** Position, velocity, and acceleration for simulated trajectories. Position is plotted as a time series while velocity and acceleration are plotted against distance to the target. In the latter plots, the target is at distance 0, on the *left* side of the plot. **a** Constant tau dot trajectories at −0.5. Deceleration grew to unrealistic values as the hand approached the target implying a crash. **b** Constant tau dot trajectories at −0.3. Deceleration reached zero at the target. **c** Constant proportional rate trajectories at 0.33. Deceleration reached zero at the target

simulations. We chose a proportional rate of 0.33. A proportional rate strategy produced similar results to a constant $\dot{\tau}_\alpha$ strategy at −0.3 and would be a plausible strategy for successful reaching. Figure 2c shows these results. The really striking aspect of all these results was that these control strategies with these relative disparity $\tau$ variables yielded trajectories that look like reaching! The control dynamics generated acceleration as well as deceleration and the resulting movement form was characteristic of reaching and, for instance, simulations thereof produced by mass-spring models of reaching. This type of behavior is not produced by previously studied monocular constant $\dot{\tau}$ models that only yield decelerative trajectories. This symmetry between forms of behavior generated by the dynamics of optical control strategies and information, on the one hand, and by the dynamics of mass-spring or EP control models of reaching (e.g. Feldman 1986), on the other hand, is potentially very significant. It means that the two types of control, one essentially optical and kinematic and the other thoroughly dynamic, are consistent with one another and mutually compatible.

A primary advantage of the proportional rate strategy is that a change in the proportional rate constant (with no other change in initial conditions) changes the timing of a reach. This can be seen clearly in Fig. 3 that shows results of simulations performed with the previous initial conditions and with proportional rate constants ranging from 0.25 to 0.5.

To test the new theory, we performed two experiments in which we investigated (1) whether participants in

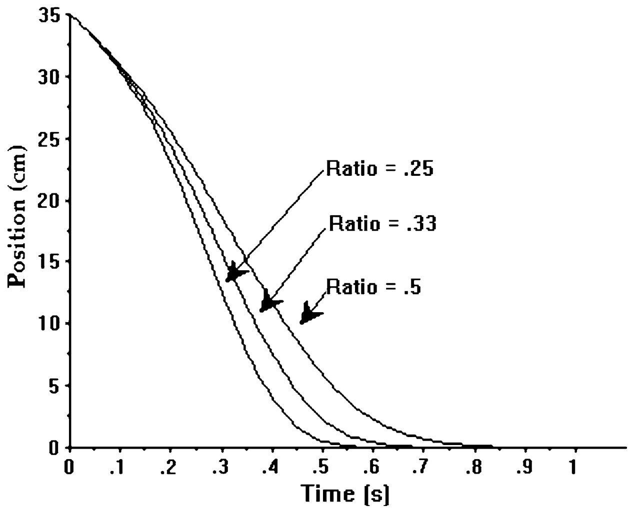


**Fig. 3** Changing the value of the constant proportional rate changes the reach timing. Position time series for three different proportional rate constants of 0.25, 0.33 and 0.5. These values represent the constant $\tau_\alpha/\dot{\tau}_\alpha$. We use $\tau_\alpha/\dot{\tau}_\alpha$ instead of $\dot{\tau}_\alpha/\tau_\alpha$ for convenience in subsequent plots

reaching tasks could use binocular disparity matching to generate accurate reaches and (2) how closely the predicted reaching profiles matched actual, human targeted reaching under conditions of binocular vision. In Experiment one, we tested the use of disparity matching using a targeted reaching task and slider apparatus that controlled for pure feedforward performance based on relative distance perception using vergence and simple mapping from visual to proprioceptive space. In Experiment two, we tested normal reaching under conditions similar to those in Experiment one so that we could analyze the trajectories and compare them to those predicted by the alternative visual control strategies. We controlled for feedforward control, based on binocular distance perception, using a new type of telestereoscope to perturb binocular distance perception and to force the use of online control if reaching was to be accurate.

## Experiment 1

The new theory requires that disparity matching be used to control targeted reaching online. We tested this. Using a specially constructed slider apparatus, participants moved a point-light in the dark to match the distance of a second, target point-light under conditions of binocular vision, monocular vision (using an eye patch to cover one eye), feedforward-only binocular vision, or fully lighted binocular vision. The point-lights eliminated all monocular depth cues, and the slider apparatus eliminated simple mapping from visual to proprioceptive space. We also tested whether binocular reaching accuracy in the dark differs from accuracy in fully lighted conditions.

### Methods

#### *Participants*

Eight adult participants (four males, three females) aged 22–52 years participated in the experiment. Participants had normal or corrected-to-normal vision, with stereo-acuity of at least 80 arcsec crossed disparity as determined using a Stereo Fly test. All participants were right-eye dominant and only one subject was left-handed. However, this subject reported no difficulty using the right-handed sliding apparatus. The data of one participant were lost due to a malfunction of the MiniBird. All procedures were approved by and conformed to the standards of the Indiana University Human Subjects Committee.

#### *Apparatus and procedure*

Participants were required to slide a point-light to match the distance in depth specified by a second, target point-light (see Fig. 4). Participants were seated in an adjustable chair at one end of a black felt covered table (50 cm wide × 273 cm long) such that the top of their hips were just below the table's edge. The slider apparatus consisted of two, 200-cm-long optical benches placed side-by-side and lengthwise along the table. The point-light sources were generated by two, approximately 2-mm-thick fiber-optic cables attached to a small flashlight. The target light was attached to the leftmost optical bench (from the participant's view) using a matt black, wooden rod placed on an optical carriage. The target light was attached to the top of the rod such that the point-light was at eye height and centered between the participant's eyes. The sliding point-light was attached to the rightmost optical bench that was located

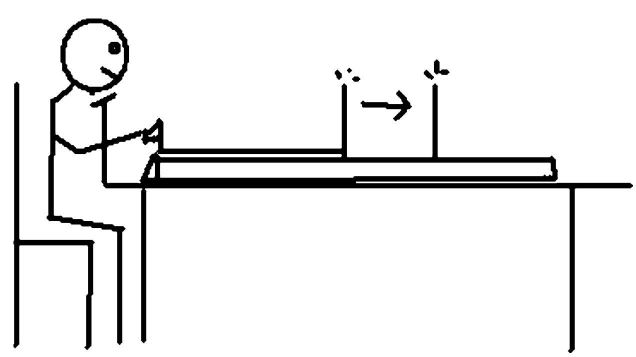

**Fig. 4** The experimental set up and slider apparatus. Participants rested their head on a chin/head rest, grasped the handle of the slider and slid the closer light to the distance of the farther light

directly adjacent to the target light optical bench. The sliding light was attached to a carriage in the same manner as the target light and the carriage was attached to a second carriage that served as the slider handle. The two sliding carriages were attached by a black wooden rod which allowed the distance between the handle carriage and the sliding-light carriage to be adjusted. During trials, the handle carriage was rigidly connected to the sliding-light carriage such that motion of the handle along the optical bench produced equivalent motion of the sliding-light. When the point-lights were aligned in depth, the distance between the sliding point-light and the target point-light was 7 cm in a frontoparallel plane. At the start of each trial, the handle for the slider apparatus was aligned in a frontoparallel plane with the participant's eyes. Participant's placed their heads on a chin and forehead rest.

Participants completed reaches with the slider apparatus under four visual conditions. In each condition, participants were asked to make one smooth, continuous reaching movement with the slider apparatus to move the sliding point-light to the same distance in depth as the target point-light. In condition one, 'binocular dark', participants reached with binocular vision in the dark. In this condition, only the two point-lights were visible at eye height. In condition two, 'monocular', participants reached with monocular vision in the dark. This condition was identical to condition one except each participants' left-eye was covered with an eye patch. In condition three, 'feedforward', participants reached with binocular vision in the dark and the sliding point-light turned off just before the reach was begun. In this condition, the target point-light was visible throughout the trial while the sliding point-light was visible only before the reach was initiated. Participants were told to reach when the sliding point-light turned off. This condition required ballistic reaching with binocular vision. In condition four, 'binocular lighted', participants reached with binocular vision in fully lighted conditions. In this condition, the apparatus was in full view of the participants and they had both binocular and monocular visual cues.

The theory predicted that reach accuracy would be good and equivalent in the binocular dark and binocular lighted conditions and that performance would be poor in the monocular and feedforward conditions.

Three target-light distances from the eye were tested with three slider-light distances for each target distance. The latter entailed adjustment of the distance of the slider light from the handle. This produced nine different starting distances and participants completed three reaching trials at each distance. These different starting distances for the slider-light decoupled the hand from the endpoint of the slider-light in depth. Under this circumstance, participants could not have used a previously calibrated, visual-proprioceptive coupling such that they could simply produce a feedforward reach to the target location by guiding the hand via proprioception. Furthermore, the slider apparatus was likely not treated by the participants as an "arm extension" in the sense of the literature on telemanipulation as participants were not allowed to heft or wield the apparatus in order to perceive its spatial characteristics. In total, participants completed 27 reaching trials in each condition. Participants were cued to begin their reach when the experimenter said "Open your eyes and reach". At the end of each trial, participants heard a short beep, which cued them to close their eyes and return the slider apparatus to the start position.

### *Data recording and analysis*

Position data were collected using an Ascension MiniBird magnetic motion measurement system. Markers were placed on the rear of each point-light bearing rod such that they were out of the participant's view but accurately recorded the spatial location of the point-lights. A third marker was placed in the plane of the participant's eye to record the eye location. Position data were recorded at 103 Hz and only $z$-position (motion-in-depth) data were used during data processing as the sliding apparatus allowed movement only along the $z$-axis. Entire movement trajectories were recorded although only endpoint accuracy was used for analysis. Data was recorded beginning approximately 2 s before reach initiation and concluding approximately one-second after reach cessation. Initiation and conclusion of data recording was controlled by the experimenter through a personal computer integrated with the MiniBird system.

All analysis on the raw data files was completed using a Matlab Version 7 program written by the authors. The program first filtered each $xyz$-coordinate set for each target using a low-pass 4th order Butterworth filter with a resulting cutoff frequency of 7 Hz. Position, velocity, and acceleration were then computed for each variable. The endpoint of the reach was determined when the velocity first dropped below 1 cm/s. Movement trajectories were only computed to provide information about the location of the endpoint of the initial reach even if participants attempted to make corrections to the reach after its conclusion. Participants were told specifically not to make corrections after the initial reach. On the vast majority of trials, endpoint location was simply the final position of the slider light with respect to the target light in the $Z$ dimension. Endpoint-only analysis was completed on these trials because the slider apparatus changed the dynamics of the reach such that any computations of $\tau_\alpha$ trajectories from the kinematics would be distorted. However, despite the slight perturbation to the movement dynamics, participants reported no problems accurately placing the endpoint of the slider apparatus at their desired location. As the goal of Experiment 1 was to demonstrate that participants could merely perform the matching task using only binocular disparity information, the slider apparatus performed well and was not a limitation to our study.

Results and discussion

As shown in Fig. 5, errors were small in the binocular dark and lighted conditions and large in the monocular and feedforward conditions. The results supported the theory because they showed that disparity matching could be used to produce accurate and precise targeted reaches and that performance was comparable under normal lighted conditions.

To examine the participants' ability to use disparity matching in the context of this task, we compared the endpoint error of reaches in each of the four conditions. To compute endpoint error, we took the absolute value of each endpoint value (measured with respect to the target position). Absolute endpoint error yields a measure akin to RMSE as a single measure that combines accuracy and precision (that is, constant and variable error). The mean error for binocular dark was 2.46 cm (standard error = 0.42 cm), while the mean error for monocular dark was 12.82 cm (standard error = 1.12 cm). A within-subjects, repeated-measures ANOVA performed on endpoint error yielded a significant difference between these conditions ($F(1, 6) = 65.34$, $P < 0.001$) (the mean constant error for monocular dark was 5.75 cm undershoot (standard error = 2.72 cm). The mean constant error for binocular dark was 1.39 cm (standard error = 0.55 cm)). The participants reported that, in the case of monocular vision, they simply slid the light outward and stopped at random as they had no idea where the target light was located in space. In fact, in some instances participants were confused about the direction in which the light was traveling with respect to their body despite their pushing the handle away from their bodies at all times. Participants were essentially reaching at random in the monocular vision case. The participant's inability to complete the task with only monocular vision combined with their personal report led us to conclude that any reaching-relevant monocular information had been excluded in this task. We successfully isolated binocular disparity information that participants must have used to complete the task.

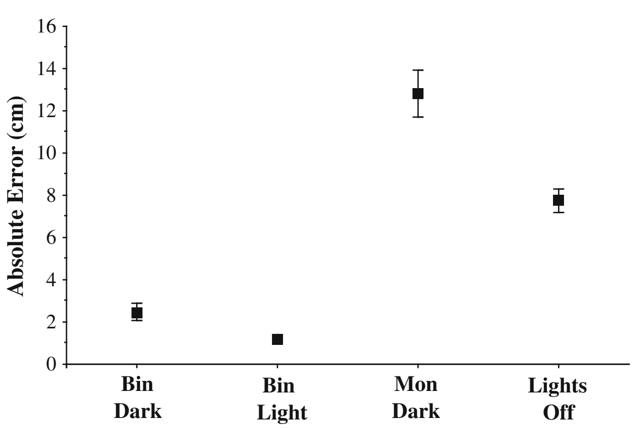


**Fig. 5** Mean absolute endpoint errors (with *standard error bars*) for each of the four conditions tested in Experiment 1: Binocular Dark, Binocular Lighted, Monocular Dark, and Feedforward

We compared endpoint error between the binocular dark and feedforward conditions to determine whether participants needed to use feedback control for accurate performance. A within-subjects, repeated-measures ANOVA performed on endpoint error yielded a significant difference between these conditions ($F(1, 6) = 78.17$, $P < 0.001$). The mean for feedforward (or lights-off) was 7.75 cm (standard error = 0.58 cm) compared with a mean of 2.46 cm for binocular dark. The mean constant error for feedforward was 6.62 cm (standard error = 0.87 cm) compared with a mean of 1.39 cm for binocular dark. It is clear that when participants were required to reach using only feedforward control after the sliding light was turned off they consistently were inaccurate. In the binocular dark condition, participants used feedback to produce accurate reaching. Given the failure of feedforward-only control and the lack of monocular information, the information used successfully in this task must have been relative binocular disparity and the control strategy must have been based on matching the disparity of the movable light to the target.

Finally, comparing binocular dark and the binocular-lighted conditions yielded an unexpected difference. A within-subjects, repeated-measures ANOVA performed on endpoint error yielded a significant difference between these conditions ($F(1, 6) = 27.92$, $P < 0.01$). However, as seen in Fig. 5, the real difference between the error in both cases is only around 1 cm especially when compared to the monocular and lights-off conditions. Participants' errors were slightly, but significantly less in the fully lighted case showing mean endpoint error of 1.19 cm with a standard error of 0.24 cm. However, the mean constant error for binocular lighted reveals that the reduction was in variability around the endpoint, not in accuracy. Mean constant error for binocular lighted was 0.81 cm with a standard error of 0.22 cm, whereas mean constant error in binocular dark was 1.39 cm with a standard error of 0.55 cm. These results suggested that participants use the same strategy in binocular dark that is used in the light, and they supported the supposition that accurate reaching is guided by disparity information. It is possible that reaching under lighted conditions reduces endpoint error by increasing the amount of binocular disparity information.

## Experiment 2

Next, we investigated the relation between actual visually guided reach trajectories and those predicted by the new theory. Participants performed otherwise normal reaches under conditions similar to Experiment 1. Our goal was to determine whether participants use a $\dot{\tau}_\alpha$ strategy to guide their reaching and if so, which one. Participants generated reaches to point-light targets in the dark under conditions of binocular vision. Participants reached under both feedback and feedforward-only conditions and under conditions of either a perturbed or normal inter-pupillary distance (IPD). The theory predicted that participants would move so as to maintain a constant proportional rate between the rate of change of $\dot{\tau}_\alpha$ and $\tau_\alpha$ itself and that this would yield the same performance levels with both normal and perturbed IPD as long as feedback control was available. Without this, we predicted significant endpoint error.

### Methods

#### *Participants*

Eight adult participants (five males, three females) aged 22–52 years participated in the experiment. Five of the participants also participated in Experiment 1, but did so more than 2 months prior. Participants had normal or corrected-to-normal vision, with stereo-acuity of at least 80 arcsec crossed disparity using a Stereo Fly test. All participants were right-eye dominant and only one subject was left-handed. However, this subject reported no difficulty using primarily right-handed reaching. All procedures were approved by and conform to the standards of the Indiana University Human Subjects Committee.

#### *Apparatus*

In some conditions, participants viewed the experimental setup through a telestereoscope. The purpose of this apparatus was to allow the experimenter to manipulate IPD and, therefore, vergence angle. Manipulating vergence angle perturbs the perceived distance of a target such that when IPD is decreased without allowing recalibration, objects in view appear farther away. Distance is specified in IPD units. When IPD is reduced by the telestereoscope, vergence returns a larger value (if IPD is reduced by half, then the value is twice as large) for a target at a given distance and if the observer is calibrated at the original larger IPD, then that vergence value is understood in the original larger units. Using the telestrereoscope, IPD units can be manipulated over a possible range of ±0.8 cm. Two flat (0 diopter) 3 cm thick plexiglass lenses were positioned in front of the eyes and rotated to achieve requisite plus or minus shifts in IPD as illustrated in Fig. 6. Reduction and increase in the size of the IPD are shown Fig. 7. The advantage of this design for the telestereoscope is that the IPD can be both increased and decreased. Usually, telestereoscopes are made with mirrors and can only increase IPD. Note that even though the Plexiglas lenses are not curved, light is refracted at the front face of the glass and therefore deviated from the straight ahead direction, traveling through the glass at that angle, and then refracted again at the back face of the glass to travel once again in its original direction (See Fig. 6). Given the 3 cm thickness of the glass, the angular deviation of the light traveling through the glass will be used to produce effective increase or decrease in the IPD, with the angle being a function of the orientation of the glass. In these experiments, IPD was perturbed from normal using the telestereoscope to decrease IPD by 0.4, 0.6, and 0.8 cm.

#### *Procedure*

Participants were required to reach to match their index finger to the distance of a target point-light. Finger position was also specified by a point-light on the finger. Participants were seated in an adjustable chair at one end of a black felt covered table (50 cm wide × 273 cm long) such that the top of their hips were just below the table's edge. The apparatus was identical to Experiment 1 with respect to the point-light sources and position of the participant with respect to the target light. The finger point-light was attached to the tip of the index finger such that, when the arm was extended and the index finger held pointing upwards with the palm facing upwards, the light faced the

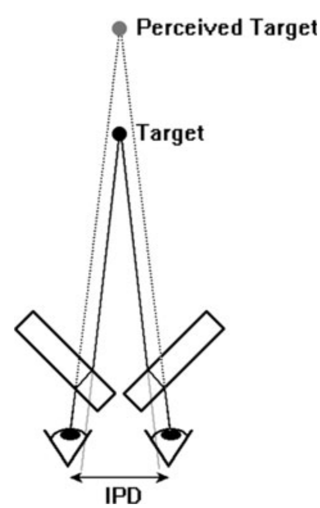


**Fig. 6** Diagram of the optical geometry of the telestereoscope. Two 3 cm thick pieces of Plexiglas displace the light path to the eye from the target with the result that vergence points to a displaced location. This is the resulting perceived distance of the target that varies as a function of the orientation of the two Plexiglas lenses

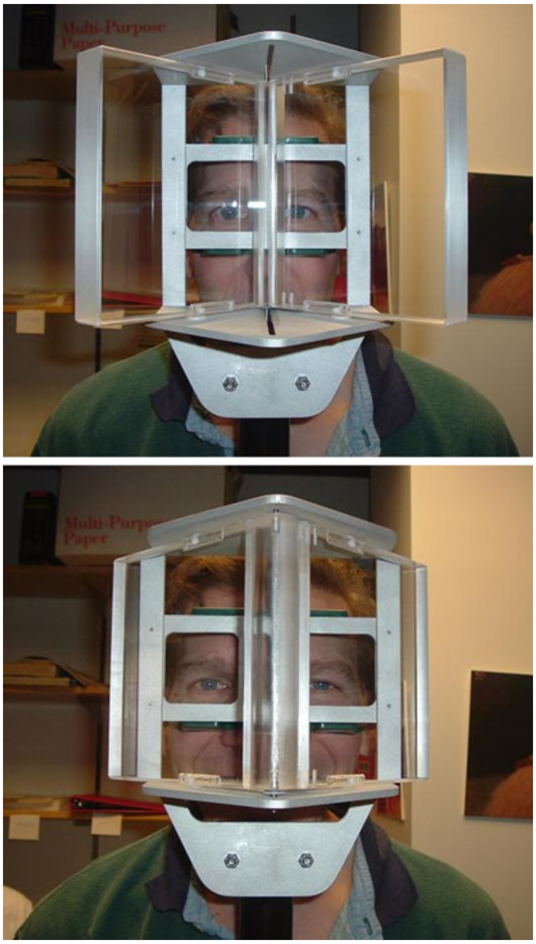

**Fig. 7** Illustration of the effect of the new type of telestereoscope. The first panel shows 'IPD in' and the second panel shows 'IPD out'. Only variations in 'IPD in' were tested in these experiments

participant's eyes. Participants began each trial with their hand placed on a pedestal aligned in parallel with and 7 cm to the right of the nose. In all cases, the target light that specified the participant's hand was out of view before reach initiation. Participants reached roughly straight to the target along the gaze axis.

3D motion data was acquired using Ascension's Mini-Bird magnetic motion measurement system. Markers for data recording were placed on the rear of the target point-light-bearing rod as in Experiment 1. A second marker was placed on the back of the index finger on the fingernail of the right hand with which they reached. A third marker was placed in the plane of the participant's eye to record the eye location.

Participants completed reaches under a number of conditions. In each condition, participants were asked to make one smooth, continuous reaching movement to bring their hand to match the distance in depth of the target point-light. Conditions included either feedforward or feedback reaching.

In the feedforward conditions, participants were required to reach toward a target light while seated behind and looking through the telestereoscope. In these conditions, participants could not see the light on their thumb and, therefore, had no visual information about hand position relative to the target. In the feedforward conditions, participants reached either with normal viewing (no perturbation to IPD) or under IPD-in settings of the telestereoscope, which perturbed IPD such that the distance between the two eyes was decreased by either 0.4, 0.6, or 0.8 cm randomly for each trial. Participants first completed 15 trials in the no perturbation condition. During the first 5 trials in this no perturbation condition, participants were calibrated such that after completing their reach and recording the endpoint location, the experimenter moved their hand to the correct target position. The following trials 6–15 were unassisted. Participants then completed 15 trials in the IPD-in condition (with random ordered variable IPD-in settings) with no calibration during those trials. Reaching in these conditions was visually open loop, that is, in the dark with no light on the finger. Participants could not see their hand. Information about the location of the hand was only available through proprioception.

In the feedback conditions, participants reached while looking through the viewing apparatus during two blocks of trials and then without the viewing apparatus during one additional block of trials. In all cases, participants were allowed to visually guide their hand to the target and hand location was specified by the point-light on the finger. In the first two feedback conditions, participants were required to reach with the viewing apparatus set either to no perturbation or to IPD-in settings identical to those used in the feedforward conditions. No calibration was performed during any of the feedback conditions. Participants completed 15 trials under the normal IPD condition. Participants then completed 30 trials in the IPD-in condition (with randomly ordered variable IPD-in settings) and 30 trials with no viewing apparatus.

In all conditions, before the start of each trial, the experimenter place the target light at a random distance away from the participant but within reach space. Participants were cued to begin their reach when the experimenter said "Open your eyes and reach". At the end of each trial, participants heard a short beep, which cued them to close their eyes and return their hand to the starting position.

*Data recording and analysis*

Basic kinematic data collection and analysis was the same as in Experiment 1. In the case of feedforward reaching in the current experiment, the relevant comparisons entailed the endpoint position of the hand in each condition where the endpoints were determined as described in Experiment 1.

As before, participants were instructed not to make corrections. Endpoints were also computed during feedback trials to assess accuracy in the same manner. In feedback trials, movement trajectories were computed to provide information about the motion of the hand with respect to the target during the trial. Reach trajectories were trimmed such that the endpoint of each trajectory was either the moment at which participant's reach velocity dropped below 1 cm/s or the point at which they passed the target.

## Results and discussion

### *Unperturbed reach trajectories: no viewing apparatus*

As shown in Fig. 8, participants reaching under conditions of visual guidance with no perturbation were accurate. Participants mean reach accuracy was −0.6 cm with a standard deviation of 0.2 cm. The negative sign indicates that participants slightly undershot the target yet were still generating well-controlled, extremely accurate reaches. In this condition, the lack of monocular information or of a fully lighted visual environment did not result in poor endpoint accuracy. Reaching using only binocular disparity matching to guide the hand to the distance of the target yielded accurate performance.

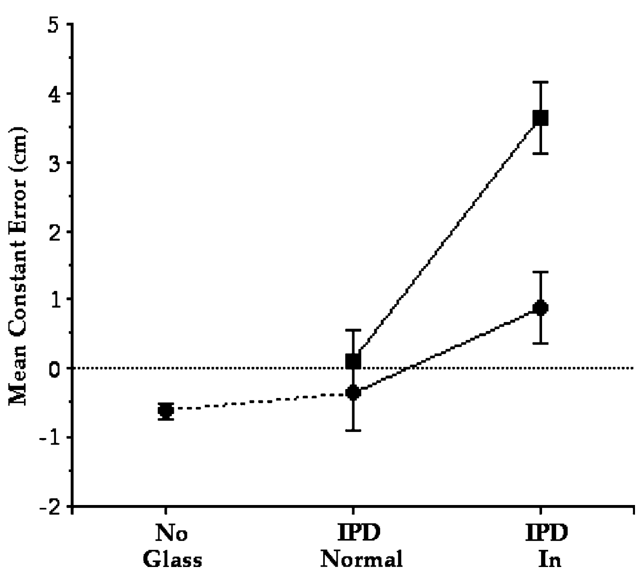


**Fig. 8** Mean constant error (with *standard error bars*) for five conditions tested in Experiment 2. Filled squares are feedforward reaches. *Filled circles* are reaches with online visual guidance. 'No Glass' is normal binocular viewing in the *dark* without the telestereoscope. 'IPD Normal' is normal binocular viewing in the *dark* with the telestereoscope set with the Plexiglas lenses in a frontoparallel plane yielding no change in IPD. 'IPD in' is a number of different settings that all reduced the IPD by various amounts. Positive errors here represent over reaching the target

In the case of unperturbed reaching with binocular-only cues, we expected participants to use either a proportional rate or a constant $\dot{\tau}_\alpha$-based strategy to control reach velocity. To reliably establish a $\dot{\tau}_\alpha$ trajectory for each reach, we computed $\dot{\tau}_\alpha$ from $\tau_\alpha$ and kinematic data in three ways and then compared the results. We computed $\dot{\tau}_\alpha$ trajectories by using our equation for $\dot{\tau}_\alpha$ (Eq. 2), by computing the first derivative of $\tau_\alpha$ at each time step, and by taking the slope of a line fit to the $\tau_\alpha$ trajectory using least squares regression. We compared the values produced by each method and found no difference.

To determine which $\dot{\tau}_\alpha$ strategy might have been used, we performed a "split-half" analysis on the $\dot{\tau}_\alpha$ and proportional rate trajectories (that is, $\dot{\tau}_\alpha/\tau_\alpha$) computed for each reach. When performing this analysis, we used the portion of the trajectory from the peak velocity to the end of the reach as determined by the trimming procedure. We then split the trajectory into two sections using the median sample point as the end of the first portion of the trajectory (near body portion) and the start of the second portion of the trajectory (near target portion). In this way, we could simply quantify the amount of change along the trajectory as participants decelerated to the target. No change in the values of near target (NT) when compared to near body (NB) would indicate that participants were maintaining a constant value of either $\dot{\tau}_\alpha$ or $\dot{\tau}_\alpha/\tau_\alpha$ whereas a difference would indicate that participants were changing the value across the trajectory. As shown in Fig. 9, mean $\dot{\tau}_\alpha$ were found to change from values near −1.0 during near body to values near −0.5 during near target, that is, the absolute value decreased.

The split-half analysis was first performed on the $\dot{\tau}_\alpha$ trajectories to determine whether $\dot{\tau}_\alpha$ was constant or changing during the movement in the no viewing apparatus condition. The mean $\dot{\tau}_\alpha$ was computed for each half in each trial. We performed a repeated-measures ANOVA on these mean $\dot{\tau}_\alpha$ for each half of the trajectories with half and repetition (the repeated trials performed by each participant) as factors. The analysis yielded a significant difference between NB and NT ($F(1, 7) = 28.15$; $P < 0.01$). Repetition and the interaction were both non-significant. As illustrated in Fig. 9, the overall mean for NB was −1.11 with a standard deviation of 0.28 and a mean standard deviation (combining SDs computed with the mean for each trajectory half) of 0.44 with a standard deviation (of those SDs) of 0.12. The mean for NT was −0.47 with a standard deviation of 0.40 and a mean standard deviation of 0.23 with a standard deviation of 0.17. Outliers in the bottom and top 10% of each distribution were trimmed when computing means. The significant difference between NB and NT indicated that $\dot{\tau}_\alpha$ was not held constant over the course of the reach. Furthermore, the overall means for NB and NT indicated a change from relatively large ($\approx 1.0$) to

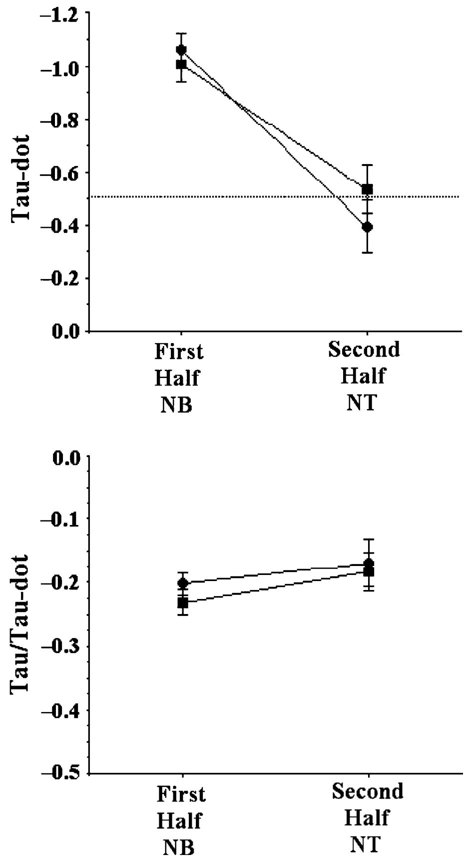


**Fig. 9** The first panel plots mean $\dot{\tau}_\alpha$ (with *standard error bars*) from the split half analyses of the trajectories in the No Viewing Apparatus (*filled circles*) and IPD in (*filled squares*) conditions. The second panel is the same for mean $\tau_\alpha/\dot{\tau}_\alpha$ (with *standard error bars*). See text for additional explanation

smaller (<0.5) absolute values of $\dot{\tau}_\alpha$. The mean standard deviation was also following this pattern by becoming smaller as the hand neared the target. $\dot{\tau}_\alpha$ drove toward zero as the hand approached the target.

One way to achieve a changing $\dot{\tau}_\alpha$ is by maintaining a constant proportional rate of change of $\tau_\alpha$ in relation to $\tau_\alpha$ itself. To determine whether participants used a proportional rate strategy, we performed the split half-analysis on trajectories generated by this proportion. We computed the mean proportion of $\dot{\tau}_\alpha$ and $\tau_\alpha$ for each half of each trajectory. Using a repeated-measures ANOVA of the same design as mentioned earlier, we found no significant difference between proportional rate values for NB and NT ($P > 0.05$). No factors or interactions reached significance ($P = 0.05$). As shown in Fig. 9, the overall mean for NB was −0.20 with a standard deviation of 0.14. The overall mean for NT was −0.15 with a standard deviation of 0.04. This lack of a significant difference between NB and NT, coupled with the significant decrease in $\dot{\tau}_\alpha$ shown in the previous analysis, indicated that participants maintained a constant proportion between the rate of change of $\tau_\alpha$ and $\tau_\alpha$ itself during the course of the reach. The overall means showed that participants maintained this constant value at about −0.18.

Although this analysis provided evidence that participants use a proportional rate strategy to guide the hand to a target visually, it did not strictly require them to *use* guidance in order to complete the task. It is possible, although unlikely, that participants may have used a completely feedforward reach to complete the task thereby never requiring $\tau_\alpha$ information for guidance. To control for this possibility, we tested participants when forced to use only feedback information. One way to achieve this was to perturb their ability to use accurate vergence information to program the initial feedforward component of the reach. Vergence angle is an important cue for absolute distance perception in a feedforward reaching strategy and it was the only distance information available in the viewing conditions in our study. A second way to control for strict feedforward performance was to test reaching with online guidance and perturbation of the distance perception that would be used for feedforward control.

### *Inter-pupillary perturbation with ballistic reaching*

To control vergence-based information about target distance, we used the viewing apparatus discussed previously to manipulate the participant's inter-pupillary distance. However, before using this apparatus for guided reaches, we tested its effectiveness at perturbing actual feedforward-only reaches. In this case, endpoint accuracy was the relevant measure of the effect of the perturbation on feedforward reaches. During the trials, participants performing feedforward reaching were calibrated with no change applied to IPD using the apparatus (apparatus normal [AN]) and then their reaching was tested under this condition. Next, their reaching was tested with a random IPD perturbation during each trial using the viewing apparatus (apparatus perturbing [AP]). As shown in Fig. 8, these feedforward reaches were accurate with AN, but overshot the target as expected with AP. A repeated-measures ANOVA yielded a significant difference in mean endpoint accuracy between AN and AP ($F(1, 7) = 25.99$; $P < 0.01$). Mean accuracy for AN was 0.20 cm overshoot with a standard deviation of 0.30 cm while the mean accuracy for AP was 3.60 cm overshoot with a standard deviation of 0.40 cm. This perturbation of feedforward reaching, yielding overshooting of the target, is consistent with the geometry of the perturbed viewing as described previously. Clearly, the apparatus worked as intended. We next used this apparatus to test participants reaching with perturbed IPD under conditions of visual guidance.

*Inter-pupillary perturbation with guided reaching*

Participants completed the reaching task with either AN or AP under conditions otherwise identical to those in the no viewing apparatus condition. In these conditions, participants were allowed visual feedback of the hand during the reach while viewing the target with AN or AP. We first examined endpoint accuracy. If participants were using feedback to control the reach, both AN and AP should have been accurate with no difference between mean endpoint values. This was the case as shown in Fig. 8. A repeated-measures ANOVA performed on endpoint errors yielded no significant difference between AN and AP in respect to endpoint accuracy ($P > 0.05$). The mean for AN was −0.35 cm undershoot with a standard deviation of 0.5 cm. The mean for AP was 0.8 cm overshoot with a standard deviation of 0.5 cm. Participants were accurate in both the perturbed and unperturbed conditions indicating that they can use visual guidance to generate accurate reaching under conditions disallowing accurate feedforward control. Also, there was no statistical difference in endpoint accuracy comparing AN to the no viewing apparatus condition using the same repeated-measures ANOVA ($P > 0.05$).

Next, we examined the $\tau_\alpha$ trajectories generated in the AP case using the split-half analysis. If participants were using a proportional rate strategy to guide their hand visually to the target, the AP condition that perturbed their ability to use feedforward control should have produced results similar to those found in the no viewing apparatus condition. As shown in Fig. 9, this is what happened. First, we computed the mean $\dot{\tau}_\alpha$ for each half of each trajectory just as we had for the no viewing apparatus condition. We found that a repeated-measures ANOVA performed on these means yielded a significant difference between NB and NT ($F(1, 7) = 13.58$; $P < 0.01$). The mean values, −1.00 and −0.53, respectively, were nearly identical to those found in the no viewing apparatus condition as can be seen in Fig. 9. Clearly, this was not constant $\dot{\tau}_\alpha$ control.

Next, we analyzed proportional rate trajectories using the split-half analysis. We found again that the AP condition was similar to the no viewing apparatus condition as shown in Fig. 9. A repeated-measures ANOVA performed on the mean proportional rate values for each half of the trajectories yielded no significant difference between NB and NT ($P > 0.05$). The mean values for NB and NT, −0.23 and −0.18, respectively, were essentially identical to those found in the no viewing apparatus condition as can be seen in Fig. 9. The overall mean values in the two conditions were −0.21 versus −0.18, respectively. Clearly, participants were generating the same proportional rate control strategy when the visual information that would be used to guide feedforward reaching was perturbed as they were when that information was not perturbed. This is an important result, but it is very much what should be expected. This, after all, is the reason that reaches should be guided online, namely to compensate for inadequacies in space perception and feedforward control. The results of the analyses supported the $\tau_\alpha$ proportional rate control theory.

*Simulations*

To test the $\tau_\alpha$ proportional rate control theory further, we used simulated movement trajectories to predict actual $\tau_\alpha$ trajectories. $\tau_\alpha$, $\dot{\tau}_\alpha$, and $\tau_\alpha/\dot{\tau}_\alpha$ trajectories representative of actual reaches and simulations are shown in Fig. 10. For each actual trial, we created a corresponding simulated trial using initial conditions taken from the corresponding actual trial together with the estimated proportional rate from that trial or the average proportional rate computed across all trials. The initial conditions in all cases included initial velocity at the start of the trimmed trajectory (peak velocity), eye distance from the target, initial hand distance from the target, and either the individual trial proportional rate or

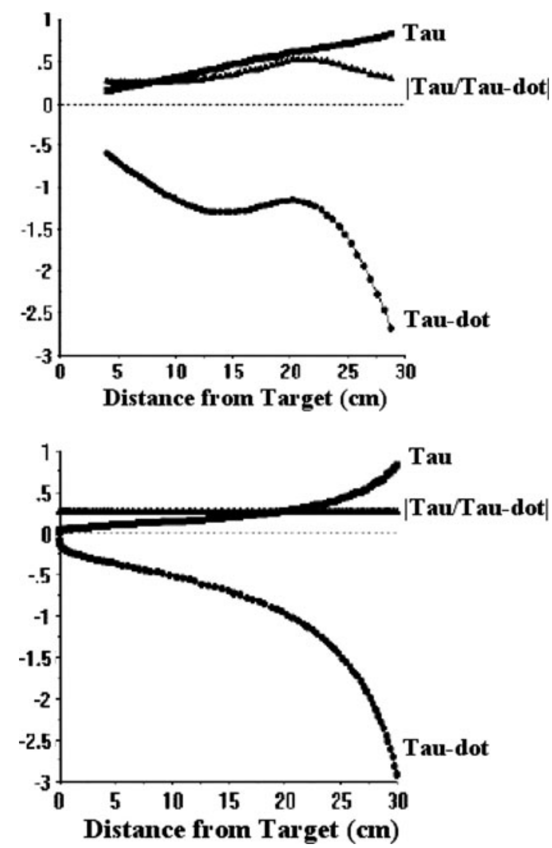


**Fig. 10** The *first panel* illustrates representative $\tau_\alpha$, $\dot{\tau}_\alpha$, and $\tau_\alpha/\dot{\tau}_\alpha$ trajectories from reaches performed in the No Viewing Apparatus condition. The *second panel* illustrates the same from simulations. The trajectories are plotted as a function of the distance from the target

the mean proportional rate. We simulated $\tau_\alpha$ trajectories for the no viewing apparatus (unperturbed) reaching case. Simulations were performed using the Simulink module attached to Matlab v7.

First, we simulated $\tau_\alpha$ trajectories using a proportional rate control strategy for the hand and initial conditions and the proportional rate estimated from each individual trial. The proportional rate for each trial simulation was the mean proportional rate from that corresponding trial. The simulations created a $\tau_\alpha$ vector for each trial and these were then correlated trial-by-trial to the corresponding $\tau_\alpha$ data vectors. We found that the mean $r^2$ value for this trial-by-trial case was high ($r^2 = 0.75$) across the 236 trials. Next, we ran the same simulation procedure using the overall mean proportional rate. Correlating the simulated $\tau_\alpha$ trajectories to their corresponding $\tau_\alpha$ data trajectories produced a slightly lower mean $r^2$ value ($r^2 = 0.72$). The relatively strong correlation between the simulated $\tau_\alpha$ trajectories and the actual $\tau_\alpha$ trajectories in both cases lent support to the hypothesis that the control strategy was a $\tau_\alpha$ proportional rate strategy.

## General discussion

To acquire a target accurately with the hand, visually guided reaching requires control based on feedback information. To date, the visual information and control strategy used to guide a reach have remained unknown. Despite this, it is clear that the primary information must be binocular and that its use must control both spatial and dynamic aspects of the task. In this work, we have proposed a new theory including a new optical information variable that people could use to visually guide their hand to a target. This information, $\tau_\alpha$, is related to the time-to-contact of two disparate images of the hand in binocular vision assuming that the actor is looking at the target, which people usually do when they reach. However, even if one were not looking at the target, this information would specify the time until the relative disparities became the same and could be used to guide the hand to a target disparity.

Our theory is that the hand is moved so as to maintain a constant proportion between $\tau_\alpha$ and its rate of change ($\dot{\tau}_\alpha$) to bring the hand to a target with soft contact. This theory offers the first solution to the problem of controlling both reach velocity and timing using visual feedback. Two previous studies employed kinematic analysis to investigate possible use of a constant monocular $\dot{\tau}$ strategy for online guidance of reaches (Hopkins et al. 2004; Zaal and Bootsma 1995). The approach used in those studies was problematic for two reasons. First, although the optical variables were not computed and analyzed directly, these studies assumed the monocular $\tau$ variable (actually, $1/\tau$) derived by Bootsma and Peper (1992). As we explained earlier, the derivation required the hand to travel along a straight path and therefore, that online corrections not entail deviations from this path. Bingham and Zaal (2004) showed that, given this assumption and for additional reasons, a monocular $\tau$ cannot be used to guide reaches. Using binocular vision and $\tau_\alpha$ as information variables for guidance, solves this problem. Second, use of a constant $\dot{\tau}$ control strategy is too limited in respect to timing. People are well known to be able to perform reaches at different speeds. It is common in studies of visually guided reaching to require participants to produce slow, medium and fast reaches and participants are able to produce corresponding movement times reliably.

Individuals using a proportional rate control strategy can modulate the timing of their reach by selecting a larger or smaller proportional value and moving so as to maintain that proportion throughout the reach. This timing flexibility derives from the fact that proportional rate control can yield acceleration and/or high rates of deceleration early on followed by increasingly smaller rates of deceleration near the end of the trajectory as shown in our simulations. This feature of $\tau_\alpha$ proportional rate control produces strikingly reach-like position, velocity, and acceleration profiles, ones that are congruent with trajectories generated by EP or mass-spring control models that, by themselves, are essentially feedforward in respect to visual control (Feldman 1986; Feldman et al. 1990; Flanagan et al. 1993; Hogan et al. 1987). An implication of this feature of $\tau_\alpha$ proportional rate control is that online guidance need not be limited to the decelerative portion of reach trajectories. A proportional rate control strategy can prescribe accelerations. EP control organization may be seamlessly integrated with $\tau_\alpha$ proportional rate control. Such smooth combination of feedforward and feedback control has been frequently observed in so-called "double step targeting" experiments that have also repeatedly demonstrated that feedback control of reaching is not restricted to the decelerative portion of reaches (e.g. Bingham 1995; Flanagan et al. 1993; Georgopoulos et al. 1981; Sondereren et al. 1988). This finding actually rules out exclusive use of constant $\dot{\tau}$ control of reaches. $\tau_\alpha$ proportional rate control is the parsimonious solution for online visual control given the results of double step targeting studies.

To investigate our theory about the role of $\tau_\alpha$ and a proportional rate strategy in guiding reaching, we performed two experiments. In Experiment one, we tested whether participants required feedback information to produce accurate reaches. We also tested whether relative disparity information was sufficient to guide a point-light accurately to a target point-light without kinesthetic information about the location of either point-light. Participants moved a slider apparatus to match the distance of a point-light on the end of the slider with a target point-light at varying distances. Participants completed this task in the dark with binocular vision, monocular vision, and in normal light with binocular vision. These conditions eliminated monocular information, isolated binocular disparity information, and allowed comparison between those two conditions and fully representative viewing conditions. Also, participants completed the binocular task in the dark under conditions in which the participant-controlled slider light went off at the initiation of the reach. This condition tested whether participants could simply use feedforward control without feedback to generate accurate reaches. They could not. Although this condition entailed special circumstances (point-lights viewed in the dark), it has been established in previous studies on visually guided reaching that individuals require feedback information about the hand to accurately acquire a target. Although there is some evidence that vergence cues can provide estimates of target distance (Mon-Williams and Dijkerman 1999), these cues were not sufficient to allow purely feedforward reaching in our task. In the guidance conditions, we found that participants were equally accurate when allowed only binocular disparity information for guidance and when allowed normal full vision. In the monocular vision, case participants were inaccurate which demonstrated that our task successfully isolated binocular disparity information. Combined, these conditions demonstrated that participants can use binocular disparity information to match the distance in depth of a target with a light guided by reaching. However, a second experiment was required to test what control strategy based on relative disparity participants might use to visually guide reaching.

Experiment two required participants to reach to a target light in the dark with both hand and target locations specified by point-lights. Participants reached to the targets with binocular vision in conditions similar to those in the first experiment that isolated relative disparity information. In some cases, participants were required to use only feedforward control, while in other cases they were allowed feedback control. In both the feedforward and feedback cases, participants' interpupillary distance (IPD) was manipulated using a telestereoscope to distort the only available distance information that could be used to program the feedforward portion of the reach. The combined function of these tasks was to isolate binocular disparity information and factor out feedforward information through distortion thereby requiring participants to use only binocular disparity-based feedback information to generate accurate reaches. In the feedfoward tasks, we found that manipulating IPD successfully distorted distance information specified by vergence and caused participants to overshoot the target when the IPD was reduced. This finding is in line with previous work by Mon-Williams and Dijkerman (1999) which demonstrated that manipulating vergence angle scaled the transport component of a reach in the direction of the changed distance although in our case we manipulated vergence angle by manipulating the IPD. In the feedback cases, we found that participants were equally accurate regardless of the perturbation to IPD and showed no decrement in performance with the telestereoscope. More importantly, we used the movement trajectories produced in the feedback conditions to evaluate the potential binocular disparity control strategies participants used to guide the hand to the target.

We used the movement trajectories to compute $\tau_\alpha$ and $\dot{\tau}_\alpha$ trajectories and the proportional rate of change of $\tau_\alpha$. We found strong support for the theory that participants move using a constant proportional rate strategy, not a constant $\dot{\tau}$ strategy. Comparing $\dot{\tau}_\alpha$ in the first and second halves of the reach trajectories, we found that the $\dot{\tau}_\alpha$ decreased reliably as predicted by proportional rate control. Finally, simulations of reaching using a proportional rate control strategy with initial conditions taken from our data showed that a proportional rate control model fit actual reaching trajectories well.

A proportional rate control strategy has a number of distinct advantages when compared to a constant $\dot{\tau}$ strategy. First, a proportional rate strategy allows flexibility where a constant $\dot{\tau}$ strategy is rigid. Proportional rate control does not result in crashing into the target when the constant proportion chosen is slightly different from the constant proportion actually produced. A proportional rate control strategy allows for imprecision. Flexibility yields stability. The result is that the constant proportional rate strategy is more stable. In a constant $\dot{\tau}$ strategy, changes in initial movement conditions force changes in the timing of the reach if one hopes not to crash. However, in a constant proportional rate strategy, actors can compensate for changes in initial movement conditions to preserve a specific timing interval as well as respond to changes in their brake's capability by selecting a different constant proportional rate values. Actors would need only to calibrate the space of proportional rate values to their brake's capability to then use different proportional rate values to modulate the timing of their movement.

In conclusion, we presented a new theory of how the reaches are visually guided online. The theory included a new information variable, $\tau_\alpha$, and a new control dynamic, proportional rate control, in which $\tau_\alpha$ is used to bring the hand to a stop at the position of a target object with flexible timing determined by a proportional rate constant. We tested this theory in two experiments. The experimental results supported the theory. Previous research has shown the importance of binocular disparity for the online control of reaching but until now a viable disparity-based control strategy has remained unknown. The current work shows how this fundamental problem in human action might be solved.

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