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CHAPTER 16

Why τ is Probably not Used to Guide Reaches

Geoffrey P. Bingham

Indiana University, Bloomington, IN

Frank T.J.M. Zaal

Vrije Universiteit, Amsterdam, The Netherlands

ABSTRACT

We suggest that τ may not be used to guide reaches. The reasons are: (1) targeted reaching is an intrinsically spatial task that requires information about length dimensioned properties (i.e. object distance, size, and/or velocity); (2) τ is time dimensioned and thus provides no spatial information. A τ variable can be constructed from perceived spatial variables and then used in a control dynamic for reaches. However, this is more complex than simply using the measured spatial variables directly in a dynamic to control reaches. Furthermore, because the control dynamic determines the timing of the behaviors, the expectation that τ might be used specifically for timing is undermined. Finally, (3) τ is unstable because the hand can slow to near zero velocities while still at significant distances from a target and, as a result, τ grows large without bound. When used as a driver in a control dynamic, τ can send the system spiraling into instability. This problem can be mitigated somewhat, but its better to simply avoid it by not using τ.

1. The main point

In this chapter, we consider whether τ might be used in the online guidance of reaches. We suggest that it is not used to guide targeted reaches. One of the original arguments for the use of τ was that τ is a temporal variable and as such, τ is appropriate for controlling the timing of behaviors, especially interceptive behaviors. If we restrict consideration to interception of target objects by the hand, then we will distinguish two fundamentally different types of situations. In one situation, the target travels towards the observer and the problem is to time the initiation of the grasp to capture the object successfully. This is a prototype situation for the use of τ and we have no argument with this. In the other situation, however, the target object either sits unmoving or travels away from the observer and the problem is to reach with the hand to the location of the target.[1] This is the problem case. As discussed in chapter by Bingham in this volume, another of the original arguments for the use of τ is related to τ's temporal dimensionality. The ability to use τ means that the classic measurement problem in space perception can be avoided. Optical structure is angular and temporal. The length dimension is lost in the projection from surface structure to optical structure. This is the origin of problems like distance perception and size perception. For the solution of timing problems that only require information about time, the problem of spatial measurement can be avoided by using τ. Following the same argument, however, τ provides no information about spatial properties. In the case of a projectile approaching an observer at constant velocity, τ only provides information about time-to-contact. It provides no information about object size, distance or velocity. The object could be large, far away and moving fast or small, nearby and moving more slowly.

The problem is that reaching to the location of a target object is an inherently spatial task. Measurement of lengths or length dimensioned properties is unavoidable. This was shown, for instance, by Bingham and Pagano (1998) who measured targeted reaches under various visual conditions. A control condition prevented participants from obtaining visual information about the distance of a target object. In this case, participants brought the hand up immediately in front of the eye so as to occlude the target, and then they moved the hand outwards at a steady slow speed, while keeping the target occluded, until the hand simply contacted the target. The time at which the hand contacted

[1] There is an intermediate situation in which the target is traveling towards the observer so as to pass within a reachable proximity, but not so as to hit the eye. Assuming that the eye is not moved to an interceptive location (as in solutions to the "outfielder problem" (Michaels & Oudejans, 1992; McBeath, Shaffer & Kaiser, 1995; McLeod & Dienes, 1996; Oudejans, Michaels, Bakker & Dolne, 1996), and that the hand is sent out to intercept the target, then this is essentially the same as the second situation. (See e.g. Peper, Bootsma, Mestre and Bakker (1994).)

the target could not be anticipated and furthermore, if the target was located beyond reach, participants would only have stopped when they ran out of arm. This manner of reaching is not representative of normal reaching. Bingham (1995) discussed ways that τ might be used in visually guided reaching and showed that length dimensioned variables must be incorporated into the use of τ variables. As also shown by other investigators (e.g. Bootsma & Peper, 1992), the trajectory of a reach to a target can be decomposed into two components: One in a frontoparallel plane and another in depth. It is the depth component that requires the length dimension. Bingham (1995) showed how, for instance, information about the size of the target relative to the size of the hand is required to derive an effective τ variable for the depth component. The requirement for length dimensioned information may be fulfilled via other means (e.g. information about definite distance), but fulfilled it must be.

Consider the case of reaching to intercept a target object that is moving away from the observer. The images of both target and hand would be contracting, so there would be a τ for each one. The signs would be opposite to those for trajectories approaching an observer, but no matter. Under conditions of constant velocity, the τ 's would specify time since departure from the eye location, but this situation does not entail constant velocities. In fact, this situation nearly always involves radically changing velocities. But we can put this aside and consider a case in which we presume unrealistically that both the hand and target are moving at constant velocities. Given only optical τ's as information, the observer does not know what the velocities are, or how far away the hand and target are. The hand's position and movement may be known via other means (e.g. somatosensory information), but not the target's. This is the crux. The target could be near and moving slowly or far and moving rapidly. Shrinking the difference in τ's (here, the difference in times-since-departure) does not yield convergence of hand position on target position. The τ's could be the same, but the velocities and positions radically different.

Could be used to guide the hand to a target moving away from the observer, but the derivation of a suitable τ would entail length dimensioned information just as in the case of reaching to an unmoving target. But it is worse. Not only would information about target size or distance be required, but in addition, information about target velocity is needed. A final criticism will be that τ is unstable when used in a control dynamic to drive the hand to a target. Given this, its reasonable to consider whether τ would be used at all instead of simply using the distance and velocity information which is required in any case. One reason that τ might still be used has been suggested by Zaal, Bootsma and van Wieringen (1998) and that is to coordinate the timing of grasping with reaching. We will return to this possibility after describing some data and some simulations of visually guided reaching that illustrate the points made thus far.

2. Mass-spring control and models of visually guided reaching

Its now fairly well established that the control of the limbs in discrete reaching is accomplished by controlling the limb as a tunable damped mass-spring with an adjustable stiffness, k, and equilibrium point, x_{ep} (Bizzi, Hogan, Mussa-Ivaldi, F. & Giszter, 1992; Feldman, 1980; 1986; Feldman, Adamovich, Ostry & Flanagan, 1990; Hogan, Bizzi, Mussa-Ivaldi & Flash, 1987; Latash, 1993)[2] :

$$m\ddot{x} + b\dot{x} + k(x - x_{ep}) = 0$$

where x, x-dot, and x-double dot are position, velocity and acceleration, respectively, m is mass, b is damping, k is stiffness, and x_{ep} is the position of the equilibrium point. The role of visual information would be to determine the behavior of the equilibrium point by acting as a driver, $G(k\ x_{ep})$:

$$m\ddot{x} + b\dot{x} + k(x) = G(kx_{ep})$$

So, the task becomes to position the equilibrium point at the target and the dynamics of the mass-spring determines the timing. The G function will also contribute to the timing, but the fact that timing is constrained by the mass-spring dynamics undermines one of the reasons for the use of τ in the driver. We will consider two alternative models that vary in terms of G.[3] The first model incorporates τ in the driver. This model essentially instantiates the ‘constant τ’ strategy hypothesized by Bingham (1995). The strategy is appropriate for controlled approach situations in which others (e.g. Yilmaz and Warren (1997))

[2] It has also been suggested that reach trajectories are limit cycles, that is, that reaches exhibit trajectory stability as well as endpoint stability (Schöner, 1994; Zaal, et al., 1999). Limit cycles are only generated by nonlinear dynamics. The driven mass-spring could be nonlinear depending on the form of the driver. (See, for instance, the chapter by Bingham in this volume.) However, a driver could also be linear. A linear mass-spring with a moving EP can yield a trajectory stability that is derived from the postural stability of the moving EP. The empirical problem is to discriminate among these possible types of trajectory stability. There is evidence for trajectory stability that comes from the postural stability of a moving EP (Won & Hogan, 1995). On the other hand, if the EP is assumed in this case to be driven externally (that is, by a motor program), then this understanding is undermined by results showing that limb movements exhibit phase resetting in response to perturbations (Kay, Saltzman & Kelso, 1991).

[3] Other models are possible and in fact, exist (e.g. Schöner (1994), Zaal, et al. (1998), Zaal, et al. (1999)). However, the models we use are sufficient to illustrate general points about alternative perceptual variables that might be used in these models. The conclusions extend to the other possible models.

have hypothesized that Tau-dot might be used. The ‘constant τ’ strategy is just that, to move so as to preserve a constant τ value, for instance, 200 ms. In strictly mathematical terms, this yields a Zeno’s paradox type situation in which one never reaches the target: “I am going to get there in a fifth of a second....I am going to get there in a fifth of a second....” and so on ad infinitum. But this also yields a straight trajectory on the phase plane (or state space, i.e. a plot of v versus x) into the origin (that is, the target) with a slope of $1/\tau_c$. As shown by Bingham (1995), this converges to an arbitrarily small distance from the target in arbitrarily small time depending on the value of τ_c. Soft contact can be achieved either by physiological tremor or by aiming just inside the target. The model we used is not a pure ‘constant τ‘ model, but it is closely related. The model is:

$$m\ddot{x} + b\dot{x} + kx = k\int g(\tau - .2)dt \qquad (1)$$

where

$$\tau = \left[\frac{x_T - x}{\dot{x}_T - \dot{x}}\right]$$

and x_T is target distance, x is the distance of the hand, $\dot{x}_T$ is target velocity, and $\dot{x}$ is hand velocity. In cases where the target object is unmoving, $\dot{x}_T$ is zero and τ reduces to $(x_T\text{-}x)/\dot{x}$. Essentially, this system tends to drive the integrand to zero (thus, it drives τ to .2). If the integrand were simply equal to τ, then this system would act to drive τ to zero. (Although this strictly qualifies as a ‘constant τ’ strategy with $\tau_C = 0$, it also corresponds to the more generally expected use of τ for targeting, that is, simply drive τ to zero for soft contact and target acquisition). The problem in this case is that $(x_T\text{-}x)$ (the distance of the hand from the target) is constrained, but $\dot{x}$ (hand velocity) is not. τ can be made to approach zero simply by driving $\dot{x}$ arbitrarily large. The result is unstable. Driving τ to a constant non-zero value (e.g. .2) yields another constraint so that $\dot{x} = (x_T\text{-}x)/\tau_c$. That is, $\dot{x}$ is proportional to the remaining distance to the target (and therefore, does not go arbitrarily large). Thus also, we see an approximately straight trajectory in phase space into the origin with a slope of $1/\tau_c$.

The τ in equation (1) cannot be specified optically simply by τ‘s projected from hand and target. Spatial or length dimensioned quantities specific to target distance and velocity are required. An apparent exception to this is a version of τ derived by Bootsma and Peper (1992) to model guidance of a hand to a target. However, their derivation required that the hand move along a straight path to the target. This, in turn, entails three conditions. First, reaches must exhibit straight paths. Often they do, but equally often they do not. For instance, the reaches in our experiment shown below did not follow straight paths. Second, the location of the target must be known, that is, the distance and direction of the target relative to the hand must be known in advance. This, by itself, is not so troubling and simply conforms to the assertion that target distance must be perceived. The third condition is more problematic. It is that the target location must be known accurately. Any error in estimation of the target location will generally require for correction departures from a straight reach path. As soon as the reach trajectory departs from a straight path, the τ variable derived by Bootsma and Peper (1992) becomes invalid. One of the reasons some form of online visual guidance is generally expected is that distance perception is known to be inaccurate (e.g. Bingham & Pagano, 1998; Bingham, et al., 2000). The τ variable in question fails exactly when it is most needed. Finally, the derivation fails when the hand is traveling directly between the eye and target, but reaches can be performed equally well approaching a target from this direction as from any other direction.

Without doubt, reaching requires perception of the target distance (x_T) (even if that perception is inaccurate). In principle, an initial assessment of target distance can be used to obtain target size (s_T) from target image size (I_T): $s_T = x_T * I_T$. Subsequently, target size can be used to obtain target distance from image size: $x_T(t) = s_T * 1/I_T(t)$. Similarly, target velocity can be obtained from target τ_T: $\dot{x}_T(t) = x_T(t) * 1/\tau_T$. Hand distance and velocity can be derived similarly (if not obtained from somatosensory sources). But, given the necessity to obtain such length dimensioned quantities visually, it is not then necessary that they be used to construct a τ variable for control. To the contrary, they could be used directly in a control dynamic.

An alternative model entails use both of relative distance between hand and target and of target velocity:

$$m\ddot{x} + b\dot{x} + kx = k\int \left[g\,\frac{(x_T - x)}{x_T} + \dot{x}_T \right] dt \tag{2}$$

The assumption that the relative distance between the hand and target is perceived is much less problematic than an assumption that the definite distance must be perceived continuously, rapidly, and accurately. Nevertheless, the model assumes that definite target velocity is perceived and this remains a worrisome assumption.

Both of these models (equations (1) and (2)) are realizations of Zaal, Bootsma and van Wieringen's (1999) suggestion that reaching is simply performed in an inertial reference frame determined by the target. The visual information is used effectively to perform a Galilean transformation, that is, a change of coordinate systems.

3. Simulations: Reaching to moving targets

Using these two models, we performed simulations of reaches to moving targets. We also tested two closely related models that are the same as those in equations (1) and (2), but with the $\dot{x}_T$ terms removed from each, respectively. With this, they loose their Galilean character, but relatedly, only information about target distance, not velocity, is required. Perhaps these models might be adequate. We will refer to the latter simplified models as (1a) and (2a), respectively.

We also performed simulations of reaches to unmoving targets and 'double-step' targets. The 'double-step' targets changed instantaneously to somewhat nearer or farther locations after a reach was initiated. We will return to an account of these results subsequently. First, we will focus on reaches to moving targets.

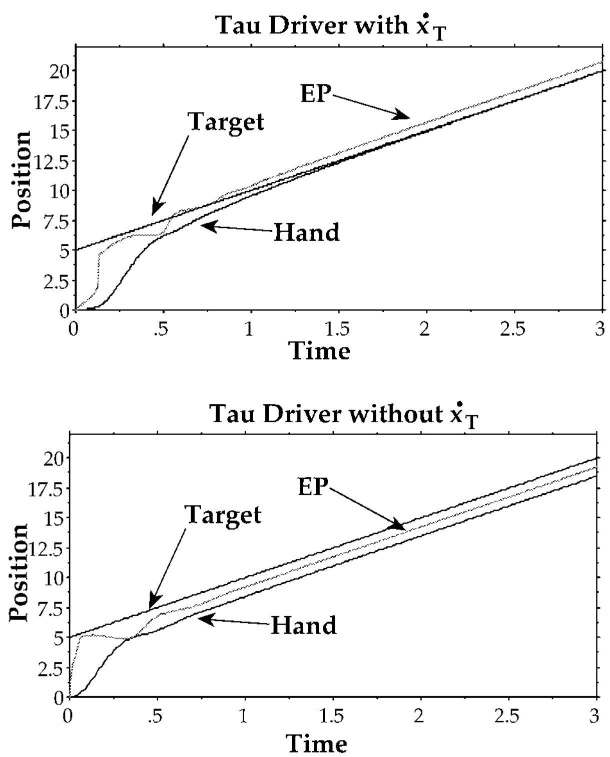

Figure 1.

In all simulations, the target lay initially at a distance of 5 units and started moving at 5 units per second at initiation of the reach. Performance of model (1) is shown in the top panel of Figure 1 where position time series are shown for the target, the hand, and the equilibrium point. The hand successfully closed on the target in about 1.5 seconds and then continued to track the target stably. The same pattern occurred with somewhat slower and faster target speeds although target acquisition occurred a little sooner or later, respectively. The performance of model (1a) is shown in the bottom panel of Figure 1. In this case, the hand never converged to the target, but instead settled at a distance from which it tracked the target. Once hand velocity was equal to target velocity ($\dot{x} = \dot{x}_T$), then the distance at which the hand remained from the target was determined by $\tau_c * \dot{x} = x_T - x$. The faster the target moved, the larger the distance. The tracking distance could be reduced by reducing τ_c, but the smallest value of τ_c that admits stable behavior is limited to about 200ms by delays within the system. The bottom line is that the τ based model cannot acquire a moving target unless τ is derived using both target position and velocity to determine a τ for the hand in a target frame of reference.

The top panel of Figure 2 illustrates the performance of model (2). The hand closed on the target within 1.25 seconds and then stably tracked the target. Again, the pattern was the same at slower and faster target speeds. The middle and bottom panels show the performance of model (2a). In both cases, the model failed to track the target. This occurred because the relative distance grew smaller (and weaker as a driver) as the absolute distances became larger, so the absolute distance between the hand and target also grew. As shown in the bottom panel, with an increase in the gain of the driver, the hand can catch the target, but it is unstable because it also fails to track. So, once again, information about both target position and velocity is required for the hand to be able to stably acquire and track the target. In this case, however, only the relative distance between hand and target (i.e. proportion of the total target distance) was required. Nevertheless, absolute target velocity was needed.

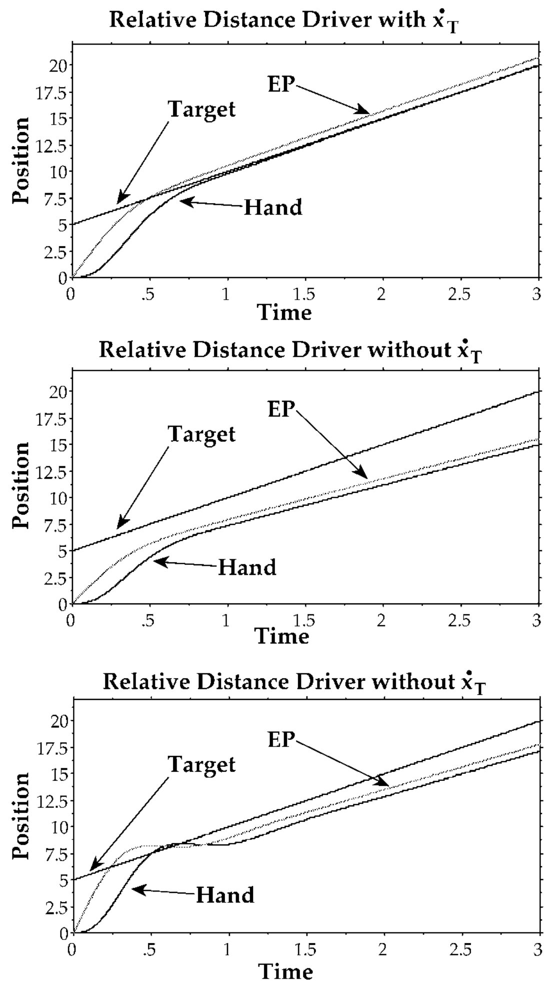

Figure 2.

4. Human performance: Reaching to moving targets

How well do people actually perform a task like this? We tested participants in a task illustrated in Figure 3. A seated participant held down a button with his right index finger. The button was located at the front edge of a flat bed plotter on which was positioned a movable target. The target was an upright wooden dowel with a wooden triangle flag projecting from it. The dowel had velcro on its top as did the participant on his index finger. The dowel sat inserted in a short pipe from which it was to be removed by the participant by reaching to contact the velcro on the top and then lifting it. The pipe ensured that the dowel had to be lifted straight upwards for successful acquisition. Hand and target movement were recorded by a Watsmart optoelectric kinematic measurement system. Infered diodes (IREDS) were placed on the participant's index finger, on the flag of the target, and immediately below the target dowel on the carriage supporting the target. The positions of the IREDS were sampled at 100 hz. Participants performed 170 trials in which they reached to acquire the target. On each trial, one of a number of possible events could occur. First, the target was positioned at one of three initial distances: Near (15cm), Medium (20 cm), Far (25 cm), or Very Far (50 cm). Second, the target might (a) remain unmoving, or (b) jump at 1 meter/second from Near to Medium, from Far to Medium, or from Medium to either Near or Far distances, or (c) move away from any of the Near, Medium or Far initial locations at one of three possible speeds: 20 cm/s, 30 cm/s, or 40 cm/s. Jumps or movement of the target started 100 ms after the participant initiated the reach and left the button. As shown in Figure 3, targets moved away in the x direction and when acquired, targets were lifted upwards in the z direction.

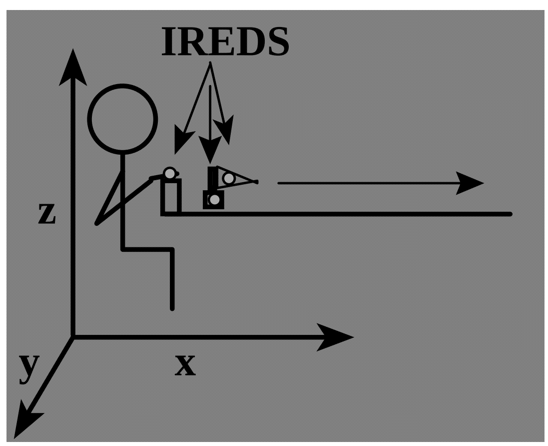

Figure 3.

Representative performance in acquiring a moving target moving at the fastest velocity (40 cm/s) is shown in Figure 4. The blue line is the finger, the red line is the target position (carriage IRED), and the green line is the flag IRED (which was above and slightly beyond the carriage IRED). In the x, the finger can be seen to acquire and track the target while in the z, the finger hovers above the target while tracking it and then moves down to contact the top of the target and then lift it from the pipe. Once the target dowel is clear of the pipe, movement of the finger and target in the x stops. The x component of this performance was well simulated by models (1) and (2).

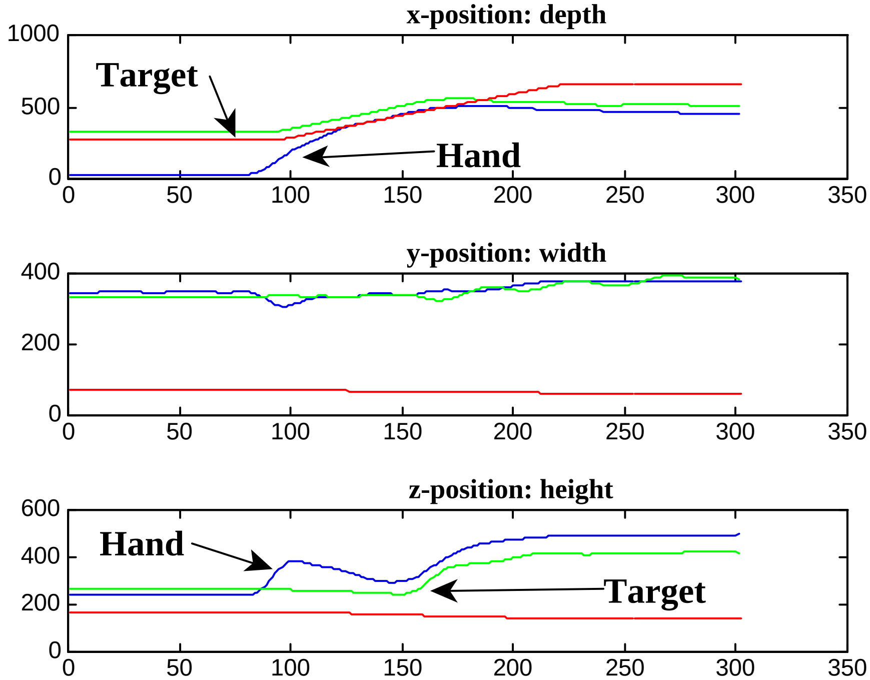

Figure 4.

5. 'Double-step' targeting and the instability of τ: A final weakness

The final weakness of the idea that τ is used to drive a reach to a target is revealed in simulations of 'double-step' targeting experiments. In 'double-step' targeting, the position of the target is changed suddenly while the hand is moving towards the target. The problem is that τ is unstable. τ becomes small as the hand approaches a target because both the distance of the hand from the target and the velocity of the hand relative to the target become small. When the target is suddenly moved to a larger or smaller distance from the hand, the distance becomes relatively large but, due to the inertia of the hand, the relative velocity remains small and near zero (after a brief, pulse-like increase in the relative velocity due to the sudden movement of the target). Sometimes the hand must reverse its direction of movement because it has passed the target. Again, hand velocity goes through zero while distance from the target remains relatively large. A very small number divided into a large number yields an exceptionally large number. τ grows without bound. The hand is sent spiraling into instability. This problem is general. Whenever the hand slows to small velocities or stops while still at significant distance from a target, this behavior will result.

We simulated a 'double-step' reach using model (2) which uses relative distance information. The target at distance 5 jumped to a near location at distance 3 at 750 ms into the reach. As shown in Figure 5, the hand overshot the nearer distance and so, reversed direction of movement. Then it slightly overshot the target again and settled to the target position.

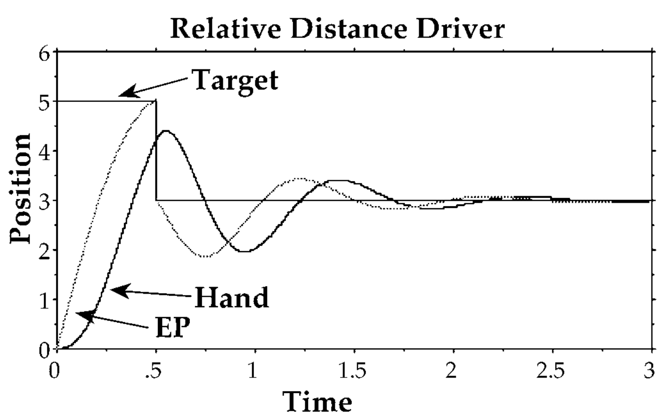

Figure 5.

Participants in the Experiment described above were also tested in 'double-step' trials in which targets moved suddenly either to a farther or to a nearer location. The reaching response is shown in Figure 6 for a trial in which the target jumped to a nearer location. The response was very like that exhibited by model (2). The hand overshot, reversed, overshot, and settled to the target location.

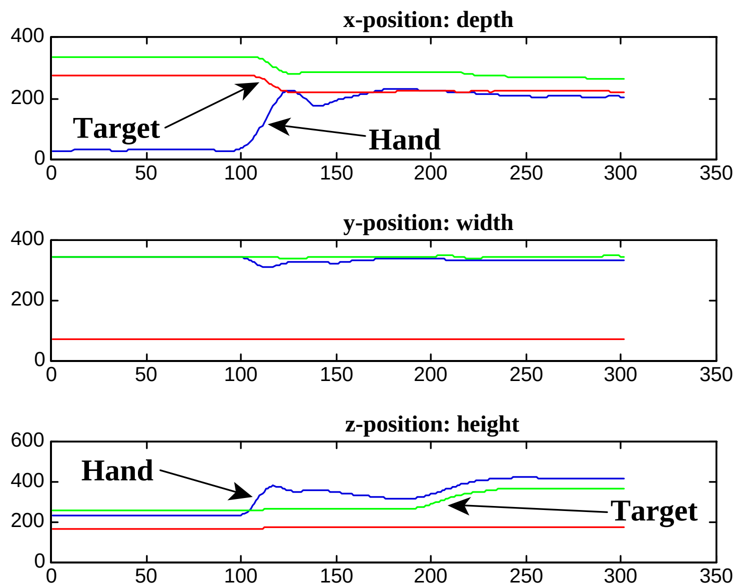

Figure 6.

Next, we tested this situation with model (2) which uses τ. As shown in the top panel of Figure 7, the hand fails to acquire the target in this case. The reason is shown in the bottom panel of Figure 7 in which the behavior of τ is shown. τ vacillates and jumps to extreme values as the hand reverses its direction of movement. This sends the hand itself into erratic movement.

This problem can be mitigated by placing τ in a saturation function that limits its ability to hit the dynamic with extreme values. We modified model (1) by replacing (τ – .2) by arctan (τ – .2). The arctan function suppresses large (+ or –) values. The resulting behavior in response to the 'double-step' perturbation was stable. The behavior was much like that of model (1) but with less overshoot as shown in Figure 8.

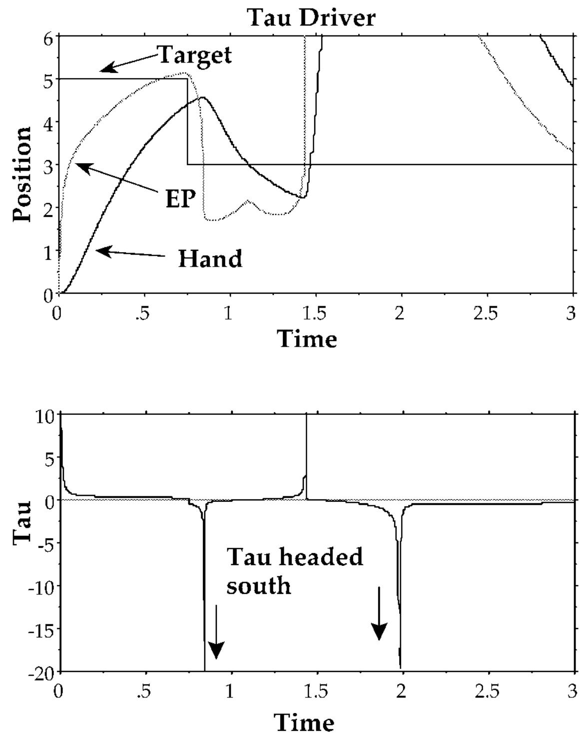

Figure 7.

The added complexity of the saturation function can be avoided, however, by simply using model (2), that is, relative distance information instead of τ.

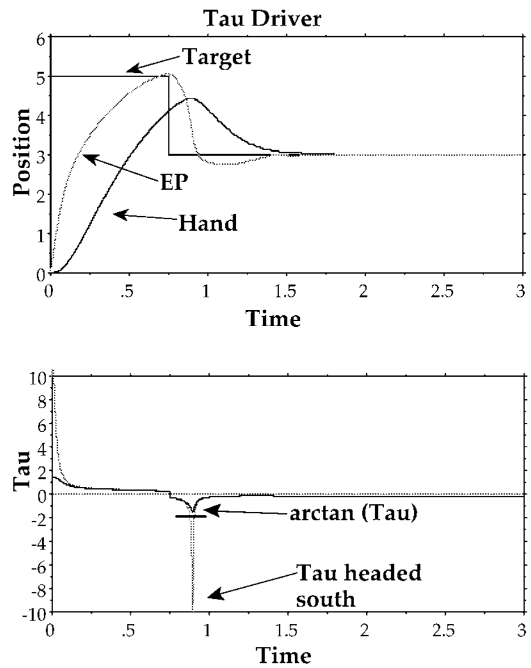

Figure 8.

6. Conclusions

Spatial, length dimensioned information about target position and velocity is required to enable reaches to acquire a moving target successfully and track it stably. It is possible to use the information to construct a τ variable that is then used to execute the 'constant τ' strategy for visual guidance. This requires information about both target and hand position and velocity. Alternatively, information about target velocity could be used together with information about the relative distance of the hand with respect to the target and this information can be used directly. The information in this case is simpler (target velocity and mere relative distance) and the model is simpler, that is, the intervening variable, τ, need not be constructed. Finally, τ is unstable as a control variable for reaches unless its behavior is modified by a saturation function. Again, greater complexity is entailed. Model (2) is the more likely on grounds of parsimony. The question is whether there are timing demands imposed by the higher dimensional aspects of reaching and grasping that might be better served by use of a τ variable. For instance, there is the issue of coordinating the frontoparallel and depth components, especially if we cannot safely assume a straight path of movement (Bingham, 1995; Bootsma & Peper, 1992). τ variables might be used to achieve the appropriate timing as suggested by Bingham (1995) and Lee (1998). (See also Lee, Georgopoulos, Clark, Craig & Port (2001).) On the other hand, the respective proportionate distances might also be used to achieve this coordination. Another coordination problem is the timing of grip opening and closing relative to the reach trajectory. Zaal, et al., (1998) have suggested that τ variables might be used independently to coordinate the timing of the grip aperture with approach to a target. If τ is being used to control grasping, then perhaps one might use it for the control of reaching as well. On the other hand, if reaching is controlled via perception of relative distance and target velocity, then perhaps grasping could be controlled independently using the same variables. That is, Zaal, et al.'s argument for use of perceptual variables in independent control structures for reaching and grasping, respectively, could simply be extended to different perceptual variables, ones that are spatial, not temporal, but potentially effective in the context of the right control structures, nevertheless.

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