ORIGINAL RESEARCH

Motor Control, 2003, **7**, 103-110

When Is Behavioral Data Evidence for a Control Theory? Tau-Coupling Revisited

Anne-Marie Brouwer, Eli Brenner, and Jeroen B.J. Smeets

Before an aspect of a movement that is predicted by a control theory can be considered as evidence for that theory, it should be clear that this aspect is not the result of some other property of the movement. We investigate whether this condition is met in studies that claim to provide evidence for the tau-coupling theory. This theory proposes that moving targets are intercepted at a specified goal zone by maintaining a constant ratio between the tau (time to closure) of the gap between the hand and the goal zone and the tau of the gap between the hand and the moving target. In line with the theory, previous research has found a linear relationship between these two decreasing taus during the last part of such a movement. To investigate whether this linear relationship was a side-effect of smooth successful movements, we modeled smooth ballistic hand movements that were independent of the target's movement but led to successful interception. We found that the resulting taus of decreasing gaps were also related linearly. We conclude that this relationship cannot be considered as evidence for the tau-coupling theory.

Key Words: time-to-contact, model testing, sensorimotor control, interception

Introduction

A theory about the way in which a kind of behavior is controlled is invalidated if data do not agree with its predictions. However, showing that data are in agreement with a theory's predictions is not enough for claiming that evidence for the theory has been found. One must be sure that the particular data pattern is caused by the proposed control mechanism and not by some other general aspect of behavior that is not specific for the theory.

An example of a theory that, in our view, has not met this requirement is the tau-coupling theory of sensorimotor control. In the present paper we will discuss this theory and argue that although the presented experimental results are in line with the theory, these results cannot be considered supportive of the theory.

Lee (1976) introduced the optic variable tau in the context of visually controlling the braking of a car. He showed that tau, in this case the inverse of the relative rate of dilation of the retinal image of an obstacle, could inform the driver

The authors are with the Department of Neuroscience at Erasmus MC, 3000 DR Rotterdam, the Netherlands. A.-M. Brouwer is now with the Max-Planck Institute for Biological Cybernetics, 72076 Tübingen, Germany.

about the time to collision at the current driving speed. More generally, tau can be defined as the time it takes for a gap to close given the present speed of closing. A large number of studies has been carried out that describe the use of tau in timing a lot of different actions such as retracting wings when diving into water (gannets; Lee & Reddish, 1981), extending legs before landing on solid ground (pigeons; Lee, Davies, Green, & van der Weel, 1993), catching (Savelsbergh, Whiting, & Bootsma, 1991), and punching balls (Lee, Young, Reddish, Lough, & Clayton, 1983). For a critical overview of studies supporting tau see Wann (1996). Other studies have proposed alternatives for the use of tau (Kerzel, Hecht, & Kim, 1999; López-Moliner, & Bonnet, 2002; Smeets, Brenner, Trébuchet, & Mestre, 1996; Tresilian, 1999).

More recently Lee (1998) generalized the tau theory, proposing that various taus of closing gaps can be coupled in order to guide movements. The gaps can be defined in any dimension, such as distance, angle, or force, and can even only be present internally (as an intrinsic tau-guide; Lee, 1998). This makes it possible to use the tau-coupling strategy for many different goal directed behaviors, such as bats' steering by echolocation (Lee, Simmons, Saillant, & Bouffard, 1995), babies' sucking from a bottle (Craig & Lee, 1999), bringing food to the mouth (Lee, Craig, & Grealy, 1999), and guiding the swing in golf putting (Craig, Delay, Grealy, & Lee, 2000).

To explain the hypothesis of tau-coupling more clearly, and to illustrate the way in which the hypothesis was tested, we will describe a paper by Lee, Georgopoulos, Clark, Craig, and Port (2001). In that study, subjects controlled a cursor to intercept a target just as it arrived in a circular goal zone on a computer monitor (see Figure 1AB). In order to succeed, all three spatial gaps in this setup [the gap between hand (h) and goal zone (g), between target (t) and goal zone, and between hand and target] must close simultaneously. This means that the taus of the three closing gaps must become zero at the same time. If the taus of two gaps become zero simultaneously, it follows that the tau of the third gap reaches zero at the same time as the other two. Therefore, a successful strategy would be to keep the decreasing tau of one gap at a constant ratio to the decreasing tau of another gap. Subjects could couple the tau of the gap between hand and goal zone (t_{hg}) to the tau of the gap between target and goal zone (t_{tg}; Figure 1A), or to the tau of the gap between hand and target (t_{ht}; Figure 1B). Lee et al. (2001) used targets moving at a constant velocity and ones moving with a constant acceleration or constant deceleration. They also varied the targets' movement times. For each trial, taus were computed for every 10 ms of the hand's movement. Lee et al. (2001) plotted t_{hg} against t_{tg} and t_{hg} against t_{ht}. The data points from the last part of the movement formed a straight line, indicating that at the end of the movement one tau was a fixed ratio of the other. This was particularly evident for the $t_{hg} – t_{ht}$ plot. They concluded that subjects guided their hands by coupling the tau of the gap between hand and goal zone to that between hand and target. The other studies that support the tau-coupling theory also do this by showing that the taus of two decreasing gaps are linearly related towards the end of the movement (Craig & Lee, 1999; Craig et al., 2000; Lee et al., 1995; Lee et al., 1999).

Of course, if you want to examine whether people couple taus of gaps in order to perform goal directed behavior, it makes sense to see whether taus of gaps are linearly related. If they were not, the theory could be rejected. However, although constant tau ratios are obviously in line with the theory, it is not self-evident that they also provide evidence for it. Constant tau ratios can only be consid-

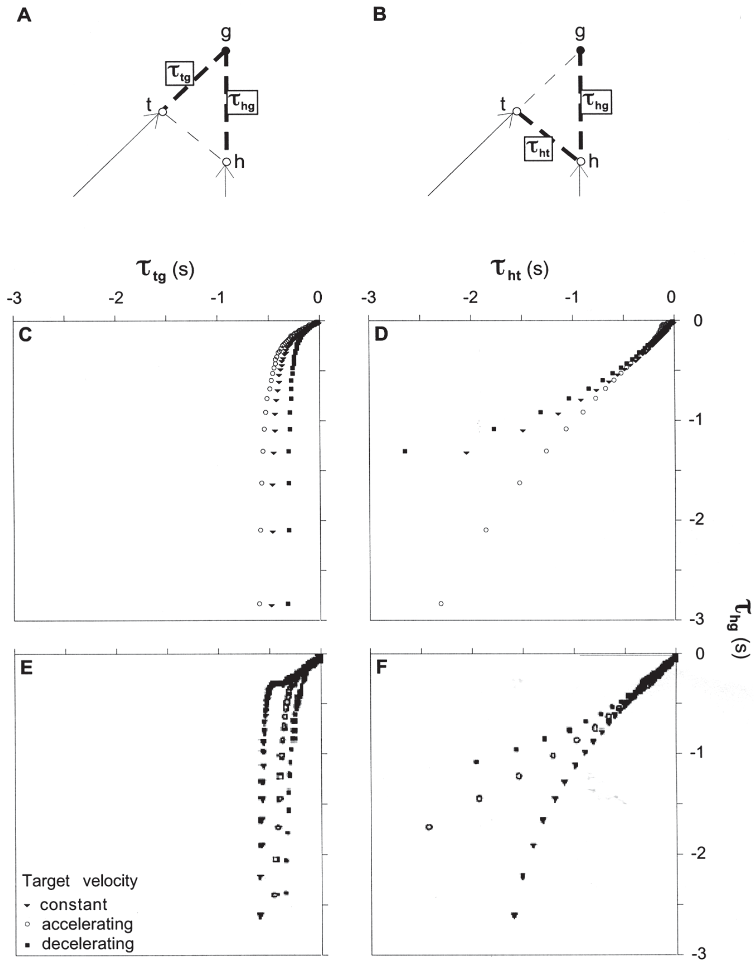

Figure 1 — The experimental task (AB) is to move ones' hand so that a cursor (h) intercepts a target (t) as it arrives at the goal zone (g). The changing tau of the gap between hand and goal zone is plotted against the tau of the gap between target and goal zone (CE) and the tau of the gap between hand and target (DF). Plots C and D present our simulated data from the condition with a target movement time of 1.4 s and a short hand movement time of 0.6 s. Plots E and F are experimental data from Figure 4G and H of Lee et al. (2001).

ered as evidence if it is clear that they are caused by subjects coupling one tau to another and not by the general movement pattern of the hand. Perhaps the data points in tau plots like those in Lee et al. (2001) converge to a straight line that intersects the zero point for any smooth successful movement. Lee et al. (2001) only considered successful trials; unsuccessful trials were repeated during the experiment until the subject succeeded. By definition, the taus of the gaps of unsuccessful movements do not decrease to zero simultaneously, whereas the taus of successful movements do, regardless of the control strategy used. Is it reasonable to expect that the data points could reach zero along a non-straight line?

Before considering a linear relationship between two taus as an argument for tau-coupling, it should be established that this relationship is not a byproduct of the fact that the movement is smooth and successful. To examine this we modeled simple smooth ballistic hand movements to the kind of targets used in the experiment of Lee et al. (2001). We generated movements for a strategy that is in conflict with the tau-coupling hypothesis. We constructed $t_{hg} – t_{tg}$ and $t_{hg} – t_{ht}$ plots from these simulated movements and checked whether the data points in these plots also converge to straight lines.

The strategy that we chose for generating smooth successful movements is equivalent to the "single shot" hypothesis mentioned in Lee et al. (2001): Watch the target, (correctly) predict when it will reach the goal zone, and move the hand without adjusting it on the way. This is not the way such movements are controlled, because we know that goal directed hand movements are continuously adjusted on the basis of visual information about the target's changing position and velocity (Brenner & Smeets, 1997; Brenner, Smeets, & de Lussanet, 1998). Indeed Lee et al. (2001) found that the skewness of the hand's velocity profile depends on that of the target; movements to accelerating targets were more skewed than those to decelerating targets. This is why they justly rejected the single shot hypothesis. Our model will thus generate speed profiles that differ from the experimental ones. However, this method allows us to compare the tau plots for smooth successful hand movements without any online adjustments (generated by the model) with movements that are adjusted online (the data of Lee et al., 2001). If both sets of plots converge to straight lines, we will have to conclude that a constant tau ratio is not an aspect of behavior that can distinguish between essentially different control theories. A constant tau ratio may not be caused by subjects coupling taus but by general aspects of the movement such as its smoothness and the fact that the movement was successful. In that case, it would no longer be justified to consider straight tau plots, such as presented by Lee et al. (2001), as evidence for coupling taus of gaps being the control mechanism in goal directed behavior.

Materials and Methods

Modeling

The modeled targets moved in the same way as the targets used in the experiment of Lee et al. (2001). They started 12.5 cm below and 12.5 cm to the left of the goal zone and moved straight toward the goal zone (Figure 1AB). The target's movement time (TMT) was 0.5, 0.8, 1.1, 1.4, 1.7, or 2 s. The targets moved at a constant velocity, with a constant acceleration (with a starting velocity of 3 cm/s) or with a constant deceleration (with an ending velocity of 3 cm/s). This resulted in 18 conditions.

The modeled hand followed a minimum jerk trajectory: It followed a straight path in space and had a symmetrical bell-shaped velocity profile. We used equation 2 from Flash and Hogan (1985) to obtain the hand's positions over time. This equation only requires the hand's movement time and its starting and ending position to generate fairly realistic ballistic hand velocity profiles. The simulated movements only varied as a function of the target's movement time and were completely independent of the target's velocity profile. Figure 2 of Lee et al. (2001) indicates that the actual movement times (MT) of the hand varied considerably. We therefore simulated a slow hand movement (MT = TMT – 0.2 s), a movement with intermediate speed [MT = (TMT – 0.2 s) 3 0.75] and a fast movement [MT =

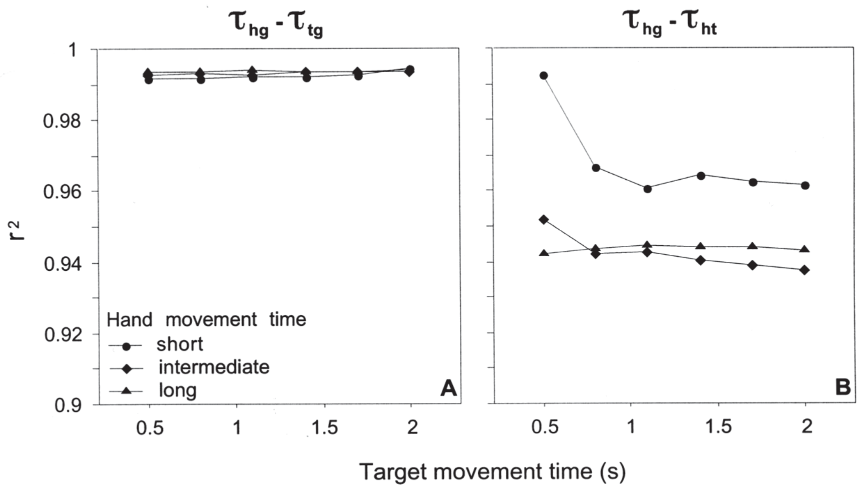

Figure 2 — R^2 values of regressions through A the final 45% of the points in the $\tau_{hg} - \tau_{tg}$ plots and B the final 63% of the points in the $\tau_{hg} - \tau_{ht}$ plots, averaged over the three velocity profiles of the target.

(TMT – 0.2 s) 3 0.5] for each condition. The value of 0.2 represents a minimum reaction time of 200 ms.

Lee et al. (2001) only considered the part of the hand's movement in which the velocity was higher than 10% of the maximal hand velocity in that trial. We therefore computed taus for every 10 ms from the time that the hand reached 10% of its maximal velocity until the time that the hand's velocity decreased to 10% again. In our simulation the hand reached the goal zone at that time, together with the target, so that the taus became zero simultaneously (as in Lee et al., 2001; see their Figure 4). The modeled hand still moved for some time (0.09 3 movement time) after the target had stopped and overshot the goal zone by 0.07 cm. Figure 2 of Lee et al. (2001) shows that their subjects also continued to move after the target had stopped.

Data Analysis

For each trial, Lee et al. (2001) determined the duration of tau-coupling as the percentage of points in the tau plots that were fit well by a straight line. To determine the strength of tau-coupling, they computed the r^2 of the regression line through these points. They found that on average, the last 45% of the data points in the $t_{hg} - t_{tg}$ plot were well fit by a straight line. This was 63% in the $t_{hg} - t_{ht}$ plot according to their criteria. The average values for r^2 were 0.983 and 0.985, respectively. Note that before computing the average durations and average r^2's, Lee et al. (2001) left out trials in which the part that was fitted well by a straight line consisted of 10 data points or less and trials in which the r^2 of the regression line was smaller than 0.95. With these criteria, they discarded 38% of the trials when t_{hg} was plotted against t_{tg}, and 20% of the trials when t_{hg} was plotted against t_{ht}.

We cannot use Lee et al.'s (2001) criteria for computing the duration of tau-coupling in our simulated movements because our model lacks experimental variability. We therefore used the same part of the data as Lee et al. (2001) and thus computed the r^2's of regression lines fit through the last 45% of the data points in the $t_{hg} - t_{tg}$ plots and the last 63% in the $t_{hg} - t_{ht}$ plots. These r^2 values cannot directly be compared to the ones of Lee et al. (2001) because we do not select trials with r^2 values higher than 0.95, and our simulated data lack experimental variability. However, our r^2 values are useful to establish a rough idea of how well our simulated movements fit the tau-coupling hypothesis and to compare the modeled outcomes between the conditions. We also judged by eye whether our tau plots converged to straight lines.

Results

Figure 1CD shows tau plots from our modeled data. These plots look remarkably similar to Lee et al.'s (2001) plots, as reproduced in Figure 1EF. The main difference is the order of the graphs of the different target velocity profiles. Lee et al. (2001) do not predict a certain order of the graphs.

The most important issue is whether the points in our tau plots converge to straight lines. Looking at the graphs, we think that they do. Figure 2 shows the r^2 values of regressions through the final part of the points, averaged across the three target velocity profiles. The average r^2 for regression lines through the final 45% of data points in the $t_{hg} - t_{tg}$ plots is 0.993, with little difference between short, intermediate, and long movement times of the hand (Figure 2A). The average r^2 for regression lines through the final 63% of data points in the $t_{hg} - t_{th}$ plots is 0.951. The points in the tau plots from the short movement time are closer to a straight line than the points from the intermediate and long movement times (Figure 2B).

The difference between the average r^2 values for the two forms of tau-coupling may be due to differences in how linear the relationship is, or it may be due to the different amounts of data that were included. To distinguish between these two possible effects we also computed the average r^2 for regression lines through the final 63% of data points in the $t_{hg} - t_{tg}$ plots and the final 45% of data points in the $t_{hg} - t_{th}$ plots. These were 0.967 and 0.958, respectively. Thus, only including 45% instead of 63% of the data increases the average r^2, but if this is taken into account, the average r^2 of the regression lines through the $t_{hg} - t_{tg}$ plots is still higher than that of the regression lines through the $t_{hg} - t_{th}$ plots.

Discussion

What this study shows is that when the analysis used by Lee et al. (2001) is performed on modeled data without adjustments of the hand's movement to the target, which is in conflict with the use of tau-coupling, the outcome meets the criteria on the basis of which these authors have claimed to have found evidence for tau-coupling in intercepting moving targets. Figure 1CD suggests that for our modeled data, the points representing the taus toward the end of the hand's movement can be approximated by straight lines just as well as the data of Lee et al. (2001; Figure 1EF). This is especially the case in the $t_{hg} - t_{tg}$ plot (r^2 values in Figure 2). If Lee et al. (2001) had found data like ours, they would probably have concluded that subjects couple the t_{hg} to the t_{tg} rather than to the t_{th}. However, as we simulated movements without online control, we know there is no active tau-coupling at all. Thus, a model that is in conflict with tau-coupling but assumes a smooth successful movement of the hand also predicts a constant ratio of taus. Apparently, a constant tau ratio is not necessarily caused by subjects coupling taus of gaps but could also be a consequence of making a smooth successful movement. We conclude that although Lee et al.'s findings (2001) are in line with the tau-coupling hypothesis, they cannot be considered as strong evidence for it.

The data of Lee et al. (2001) do show that hand movements are not completely predetermined. The finding that the hand's velocity profile depends on the velocity profile of the target indicates that the movement of the hand is adjusted during the movement. However, we do not know yet whether this online control is based on tau-coupling or, for example, on coupling the speed of the hand to the speed of the target (Brouwer, Brenner, & Smeets, 2000).

As pointed out above, a constant tau ratio does not necessarily mean that tau-coupling is used. An additional disadvantage of using linearly related taus as a critical test of the tau-coupling theory is that it is a rather vague prediction. How long should the taus be linearly related and how strongly? In principle, any short piece of a smooth curve can be approximated by a straight line, so if you only look at the very last part of the movement, the taus have to be related linearly.

Other studies that claim to show evidence for tau-coupling (Craig & Lee 1999; Craig et al., 2000; Lee et al., 1995; Lee et al., 1999) have used essentially the same analysis as in Lee et al. (2001). After a task was performed, taus of several decreasing gaps were plotted against each other, and the percentage of points lying on a straight line was determined, together with an r^2 value. The authors then concluded from this that the duration and strength of tau-coupling in (one of) the tau plots is "good". The present study suggests that this method is not the appropriate one to critically test the tau-coupling hypothesis, and therefore the conclusions of these studies should be regarded with caution.

A more general conclusion of the present study is that researchers of motor control should ask themselves the question whether a certain pattern in data observed in successful movements reflects a particular control strategy or whether it is a consequence of performing the task adequately, irrespective of the control strategy (see also Smeets & Brenner, 1999).

Additional Remarks About Tau-Coupling

The arguments presented above do not reject the tau-coupling hypothesis. They only show that we need a better way to test the hypothesis. When devising such a test, one could consider a number of additional theoretical issues as we will point out below.

The tau-coupling hypothesis as it now stands ignores neuronal delays. It is not clear how it is possible to keep the tau of the gap between hand and target proportional to the tau of the gap between target and goal zone, because it takes time to determine the value of tau, send the appropriate motor commands to the muscles, and to let the muscles contract. It seems that an implementation of tau-coupling in the brain would only be possible if future values of tau were predicted.

The idea of tau-coupling as presented in Lee et al. (2001) also depends, in our view, on an unlikely assumption if it is to be considered as a control strategy for interception in general. It assumes that subjects who intercept a moving target determine a fixed point in space where they will contact the target. There are several indications that this is not their natural strategy. First, tasks in which subjects have to intercept targets in a goal zone appear to be difficult. Lee et al. (2001) reported that subjects found their task very demanding and that performance was poor on some trials. Second, if the goal zone is not marked visually, there is no direct visual information regarding the tau between target and place of interception. Third, if targets disappear after varying times, the hitting position depends on the time that the target is visible (Brouwer, Brenner, & Smeets, 2002), indicating that the intended place of interception changes during the movement. Of course, the interception point that is used to calculate the taus could also change during the movement. However, such a model would be even more difficult to test.

References

Brenner, E., & Smeets, J.B.J. (1997). Fast responses of the human hand to changes in target position. *Journal of Motor Behavior,* **29**, 297-310.

Brenner, E., Smeets, J.B.J., & de Lussanet, M.H.E. (1998). Hitting moving targets: Continuous control of the acceleration of the hand on the basis of the target's velocity. *Experimental Brain Research,* **122**, 467-474.

Brouwer, A., Brenner, E., & Smeets, J.B.J. (2000). Hitting moving objects: The dependency of hand velocity on the speed of the target. *Experimental Brain Research,* **133**, 242-248.

Brouwer, A., Brenner, E., & Smeets, J.B.J. (2002). Hitting moving objects: Is target velocity used in guiding the hand? *Experimental Brain Research,* **143**, 198-211.

Craig, C.M., Delay, D., Grealy, M.A., & Lee, D.N. (2000). Guiding the swing in golf putting. *Nature,* **405**, 295-296.

Craig, C.M., & Lee, D.N. (1999). Neonatal control of nutritive sucking pressure: evidence for an intrinsic t-guide. *Experimental Brain Research,* **124**, 371-382.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience,* **5**,1688-1703.

Kerzel, D., Hecht, H., & Kim, N.G. (1999). Image velocity, not tau, explains arrival-time judgments from global optical flow. *Journal of Experimental Psychology: Human Perception and Performance,* **25**, 1540-1555.

Lee, D.N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception,* **5**, 437-459.

Lee, D.N. (1998). Guiding movement by coupling taus. *Ecological Psychology,* **10**, 221-250.

Lee, D.N., Craig, C.M., & Grealy, M.A. (1999). Sensory and intrinsic coordination of movement. *Proceedings of the Royal Society of London B,* **266B**, 2029-2035.

Lee, D.N., Davies, D.N.O., Green, P.R., & van der Weel, F.R. (1993). Visual control of velocity of approach by pigeons when landing. *Journal of Experimental Biology,* **180**, 85-104.

Lee, D.N., Georgopoulos, A.P., Clark, M.J.O., Craig, C.M., & Port, N.L. (2001). Guiding contact by coupling the taus of gaps. *Experimental Brain Research,* **139**, 151-159.

Lee, D.N., & Reddish, P.E. (1981). Plummeting gannets: A paradigm of ecological optics. *Nature,* **293**, 293-294.

Lee, D.N., Simmons, J.A., Saillant, P.A., & Bouffard, F. (1995). Steering by echolocation: a paradigm of ecological acoustics. *Journal of Comparative Physiology,* **176A**, 347-354.

Lee, D.N., Young, D.S., Reddish, P.E., Lough, S., & Clayton, T.M.H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology,* **35A**, 333-346.

López-Moliner, J., & Bonnet, C. (2002). Speed of response initiation in a time-to-contact discrimination task reflects the use of h. *Vision Research,* **42**, 2419-2430.

Savelsbergh, G.J.P., Whiting, H.T.A., & Bootsma, R.J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance,* **17**, 315-322.

Smeets, J.B.J., & Brenner, E. (1999). A new view on grasping. *Motor Control,* **3**, 237-271.

Smeets, J.B.J., Brenner, E., Trébuchet, S., & Mestre, D.R. (1996). Is judging time-to-contact based on 'tau'? *Perception,* **25**, 583-590.

Tresilian, J.R. (1999). Visually timed action: time-out for 'tau'? *Trends in Cognitive Science,* **3**, 301-310.

Wann, J.P. (1996). Anticipating arrival: Is the tau margin a specious theory? *Journal of Experimental Psychology: Human Perception and Performance,* **22**, 1031-1048.

Acknowledgments

This research was supported by the Netherlands Organization for Scientific Research (NWO/MAG grant 575-23 015).