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The Scaling of Information to Action in Visually Guided Braking

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Braking to avoid a collision can be controlled by keeping the deceleration required to stop (i.e., ideal deceleration) in the "safe" region below maximum deceleration, but maximum deceleration is not optically specified and can vary as conditions change. When brake strength was manipulated between participants using a simulated braking task, the ratio of ideal to maximum deceleration at brake onset was invariant across groups, suggesting that calibration involves scaling information about ideal deceleration in intrinsic units of maximum deceleration. Evidence of rapid recalibration was found when brake strength was manipulated within participants, and the presence of external forces that affect brake dynamics resulted in biases in performance. Discussion focuses on the role of calibration, internal models, and affordance perception in visually guided action.

Keywords: visually guided action, braking, perceptual-motor calibration, optic flow

Tasks such as steering, braking, and intercepting moving objects belong to a class of behaviors, sometimes referred to as *visually guided actions*, that typically require one to satisfy certain spatio-temporal constraints by guiding movement on the basis of continuously available visual information (see Warren, 1998, for a review). The conventional approach to understanding such visually guided actions is to assume that all of these tasks involve some form of error nulling (Fajen, 2005b; Warren, 1988). For each task, one could define an ideal state in which the actor should strive to be at each moment. When an actor is steering toward a goal, for example, the ideal state is the turning rate that will bring the actor to the goal without making any further steering wheel adjustments along the way. When an actor is braking to avoid a collision, the ideal state is the rate of deceleration that will bring the actor to a stop at the desired location without making any further brake adjustments. The difference between the current state and the ideal state constitutes an error that eventually must be corrected for the task to be successful. Laws of control describe how visual information is used to make such error-nulling adjustments.

Lee's (1976) $\dot{\tau}$ (*tau-dot*) model of braking is a prototypical example of a widely accepted theory that conforms to this approach (see Bardy & Warren, 1997, for an excellent review of research on the tau-dot model). $\dot{\tau}$ is the first derivative of the optical variable τ, which is equal to the ratio of the optical angle, θ, to the rate of optical expansion, $\dot{\theta}$, of the object at which one intends to stop. When $\dot{\tau} < -0.5$, the current rate of deceleration is insufficient (i.e., less than the ideal deceleration), and the actor will collide with the object unless deceleration is increased. When $\dot{\tau} > -0.5$, actual or current deceleration is excessive (i.e., greater than the ideal deceleration), and the actor will stop short of the object unless deceleration is decreased. Thus, $\dot{\tau}$ provides information about the sufficiency of the actor's current deceleration. By making brake adjustments that move $\dot{\tau}$ in the direction of -0.5, the actor effectively "nulls the error" between the current and ideal deceleration without ever having to estimate these quantities.

Early tests of the tau-dot model used linear regression to show that the slope of τ as a function of time was between 0.0 and -1.0 for hummingbirds approaching a feeding tube (Lee, Reddish, & Rand, 1991) and pigeons landing on a perch (Lee, Davies, Green, & van der Weel, 1993). However, the slope of τ is nothing more than an estimate of the mean value of $\dot{\tau}$ over the interval and reveals nothing about how deceleration is regulated on the basis of $\dot{\tau}$ (Bardy & Warren, 1997). Moreover, Wann, Edgar, and Blair (1993) found that their data (based on human participants running toward a surface) were better fitted when the approach was divided into two phases: a transport phase lasting from the onset of deceleration to about 1.2 m from the target, during which the mean $\dot{\tau}$ value was close to -0.5, followed by a homing phase at the end of the approach, for which the mean $\dot{\tau}$ value varied with the demands of the task (e.g., soft contact, hard contact, reversal). To date, the most convincing evidence in support of the tau-dot model of braking was provided by Yilmaz and Warren (1995), who used a simulated braking task to show that people tend to increase deceleration when $\dot{\tau} < -0.5$ and decrease deceleration when $\dot{\tau} > -0.5$. They also showed that performance was unaffected (except when initial time to contact was short) when cues for distance and speed were removed, which suggests that information provided by $\dot{\tau}$ alone is sufficient to control braking.

Despite the widespread acceptance of and persuasive support for the tau-dot model, there are aspects of the braking task that are critical for successful performance that this model is simply unable to capture. The problem with the tau-dot model (as well as any model based on the error-nulling assumption) is that nulling the difference between the current and ideal deceleration is a sufficient condition for successful performance but not a condition that is always possible to satisfy. Consider a scenario in which an actor waits too long to start braking. As the actor closes in on the object

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at a constant speed, the amount of constant deceleration needed to stop (i.e., the ideal deceleration) increases gradually at first and then more rapidly, until it explodes to infinity at contact. This is illustrated in Figure 1A, which shows ideal and current deceleration as a function of time for the situation in which the actor never initiates braking. Although the actor in this sample trial did not collide with the object until 3.00 s, collision was inescapable by 1.93 s—once the ideal deceleration exceeded maximum deceleration (7.0 m/s^2). In Figure 1B, ideal deceleration increased more gradually because the actor applied the brake before colliding. However, because current deceleration was increased too gradually, the outcome was the same—the actor failed to avoid a collision even though maximum deceleration was applied, because ideal deceleration exceeded maximum deceleration. Figure 1C shows a successful trial in which the actor made brake adjustments to keep the ideal deceleration between zero and maximum deceleration for as long as possible. Eventually, ideal deceleration drops to zero at the moment that the actor comes to a safe stop in front of the object.

Maximum deceleration thus defines an *action boundary* because it separates situations into two possible categories—those in which it is still possible to stop safely and those in which it is no longer possible to stop safely. As long as the ideal deceleration is maintained within the "safe" region below maximum deceleration, it is still possible to stop safely by adjusting deceleration within the limits of the brake. At the moment that the ideal deceleration exceeds the action boundary, it is no longer possible to stop. Given the significance of maximum deceleration for successful performance, one would assume that actors must be extremely sensitive to the location of the action boundary. Unfortunately, $\dot{\tau}$ provides no information about whether the ideal deceleration is above or below maximum deceleration. If actors relied on $\dot{\tau}$ to control braking, then they would be completely insensitive to the location of the action boundary and would be unable to keep ideal deceleration within the safe region.

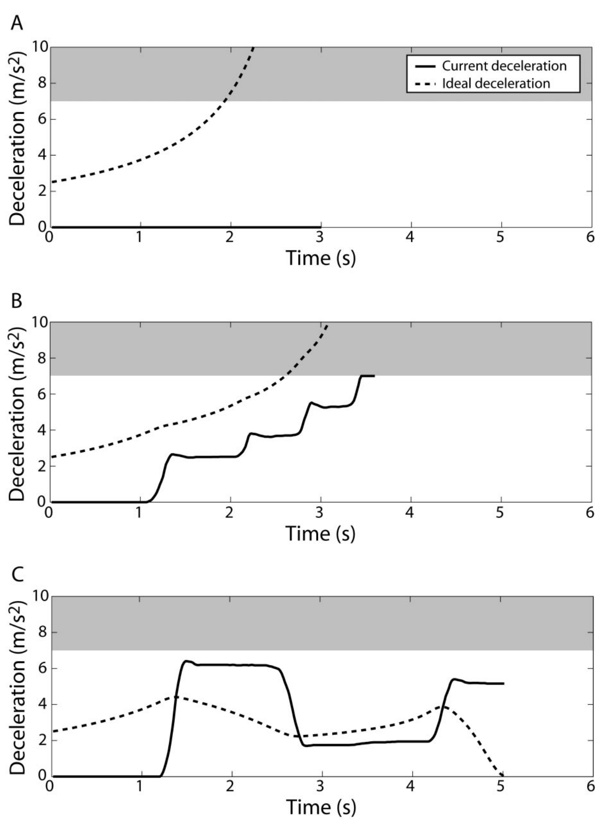

Figure 1. Current and ideal deceleration profiles from three sample trials resulting in (A) a crash due to the failure to initiate braking, (B) a crash due to increasing deceleration too gradually, and (C) a safe stop. Initial distance was 45 m, initial speed was 15 m/s, and maximum deceleration (indicated by the solid region) was 7.0 m/s^2. m/s^2 = meters per second squared; s = seconds.

The same criticism applies to any model of braking according to which actors make adjustments to cancel the difference between the current and ideal deceleration. For example, one alternative model recently proposed by Andersen, Cisneros, Atchley, and Saidpour (1999; Andersen & Sauer, 2004) suggests that actors compare an estimate of current absolute distance to the object (based on traditional cues, e.g., familiar size) with an estimate of the distance required to stop assuming current deceleration is maintained (based on cues to speed and deceleration). The difference between these two estimates specifies whether the actor should increase or decrease deceleration. The authors provided empirical support for this model by showing that judgments of collision with objects in the path of motion as well as actual braking behavior were influenced by factors such as object size and edge rate. Because neither factor affects $\dot{\tau}$, Andersen et al. concluded that cues to size and speed are used to control braking in the manner suggested by their model. Like $\dot{\tau}$, however, the difference between current distance and the distance required to stop tells actors about the sufficiency of their current deceleration and is completely independent of maximum deceleration. Thus, actors relying on such estimates to control braking would also be insensitive to the constraint imposed by maximum deceleration.

In summary, existing models of braking assume that actors rely on information about the sufficiency of their current deceleration and make adjustments to cancel the difference between current deceleration and the deceleration required to stop (i.e., the ideal deceleration). Such models ignore the most critical constraint on successful braking—that is, that the ideal deceleration must never exceed the maximum deceleration. Using a simulated braking task similar to Yilmaz and Warren's (1995), Fajen (2005a) recently demonstrated that actors make brake adjustments that are not predicted by the tau-dot model to keep the ideal deceleration below the maximum deceleration. To isolate the influence of ideal deceleration relative to maximum deceleration, Fajen's analysis focused on segments of each trial in which the difference between the current and ideal deceleration was close to zero. Because $\dot{\tau}$ is approximately equal to -0.5 in these situations, the tau-dot model predicts that actors should maintain deceleration (or be just as likely to decrease deceleration as they are to increase it) regardless of ideal deceleration. Fajen found that as the ideal deceleration approached the maximum deceleration of the brake, participants were more likely to increase deceleration.

Fajen (2005a) concluded that the only way to account for these findings was to reject the assumption, on which the tau-dot model is based, that actors make brake adjustments to null the difference between the current and ideal deceleration. Instead, actors control braking by making adjustments to keep the ideal deceleration within the safe region between zero and the maximum deceleration. This theory accounts for why actors always increase braking when the ideal deceleration is close to the maximum deceleration. Even if $\dot{\tau}$ is close to -0.5, keeping the ideal deceleration near the maximum deceleration is extremely risky. The theory also accounts for the findings reported by Yilmaz and Warren (1995) that actors appear to make brake adjustments to move $\dot{\tau}$ in the direction of -0.5. They interpreted this finding as evidence to support the tau-dot model, but the same pattern of results would be expected if actors made adjustments to keep the ideal deceleration within the safe region on both sides, as they often do (e.g., see Figure 1C). Thus, the model proposed by Fajen accounts for the previous data on braking and also explains why actors reliably increase deceleration when ideal deceleration approaches the maximum deceleration.

One important difference between these two approaches is that error-nulling models such as the tau-dot model have preferred states (e.g., the ideal deceleration) in which the actor should strive to be at each moment in time. In the new framework, there is a safe region within which the actor should remain but no preferred state within that region. One could argue that the new framework fails to provide a specific account (e.g., a control law) of how action is controlled within the safe region. However, the fact is that there are an infinite number of possible trajectories through the safe region that correspond to successful performance. Conservative actors attempt to minimize collisions by making adjustments to keep ideal deceleration near the bottom of the safe region close to zero, but at the expense of longer approach times. More aggressive actors minimize approach time by allowing ideal deceleration to rise to the top of the safe region near maximum deceleration. Some actors might attempt to minimize boredom by allowing ideal deceleration to oscillate erratically within the safe region. Although the style of control may differ, there are many ways to perform the task successfully. Therefore, it seems unlikely that there could be a single preferred state in which all actors should strive to be across all conditions. The only constraint on successful performance that is common to all situations and all individuals is that the ideal deceleration remains within the safe region. How ideal deceleration is actually controlled within the safe region depends on situation-specific factors. However, all of these factors may be understood as additional, “softer” constraints on trajectories through the safe region. In the real world, for example, the costs of collisions and high deceleration rates are considerably more significant than they are in the lab. Therefore, during real-world driving, trajectories may be constrained to the lower part of the safe region. The important point, however, is that these factors introduce additional constraints on trajectories; they do not prescribe a preferred trajectory. Adjustments are not made around an ideal state but rather within a safe region.[1]

To keep ideal deceleration within the safe region, actors must be able to detect information about ideal deceleration relative to maximum deceleration. Ideal deceleration is optically specified by a combination of global optic flow rate (GOFR) and τ (i.e., GOFR/2τ),[2] but maximum deceleration is a property of the actor’s body or vehicle for which there is no optical information. If actors perform successful braking by keeping the ideal deceleration within the safe region and the boundary of that region defined by maximum deceleration is “invisible,” then how do actors know the location of the boundary? Furthermore, maximum deceleration depends not only on the strength of the brake but also on a variety of other factors, such as load, surface friction, and surface slope. Because some of these factors can change quickly, actors must be able to rapidly adapt to such changes to control braking.

A simple solution to this problem is to scale information about ideal deceleration (e.g., GOFR/2τ) in units of maximum deceleration. The extrinsic units that are typically used by researchers to express decelerations, such as meters per second squared or eyeheights per second squared, are just as arbitrary and meaningless to perceivers as any other units.[3] If all units are equally arbitrary, then perhaps there is no default metric and perceptual systems are able to recalibrate by continually adjusting the measurement scale (i.e., the size of the units) in which information is detected. When the scale is adjusted so that it is always possible to stop when ideal deceleration measures less than 1.0 and never possible to stop when ideal deceleration measures more than 1.0, then ideal deceleration is perceived in units of maximum deceleration. Because maximum deceleration is defined by the actor’s action capabilities, these units are intrinsic rather than extrinsic. To control braking, actors simply need to make brake adjustments to keep the ideal deceleration (in intrinsic units) between 0.0 and 1.0. Of course, practice and experience are necessary to adjust the metric so that the units correspond to maximum deceleration. When one says that an inexperienced actor does not know the strength of the brake, what one means in these terms is that the actor does not have the correct metric. Information contained in the optical consequences of individual brake adjustments must be used to adjust the metric until 1.0 reliably separates possible from impossible stops. The same principle also applies to situations in which the effective maximum deceleration changes because of factors such as changing loads. When towing a trailer, for example, the driver must recalibrate to the change in maximum deceleration by detecting ideal deceleration in smaller units so that perceived ideal deceleration (in units of maximum deceleration) is greater than it was before the trailer was attached.

The primary goal of this study is to investigate the role of calibration in visually guided braking. In Experiment 1, brake strength was manipulated as a between-subjects factor and performance was compared between groups. If participants calibrate to the strength of the brake by detecting information about ideal deceleration in intrinsic units of maximum deceleration, then the ideal deceleration at the onset of brake adjustments should be the same across groups when ideal deceleration is expressed in units of maximum deceleration. In Experiments 2 and 3, brake strength was manipulated as a blocked (Experiment 2) or randomly presented (Experiment 3) within-subject factor to test the rate of

[1] Similar ideas have been expressed by Flach, Smith, Stanard, and Dittman (2004), who showed how trajectories and constraints can be represented in a state space of optical variables θ and $\dot{\theta}$.

[2] In terms of spatial variables, the deceleration required to stop (the ideal deceleration) is equal to $v^2/2z$, where v is speed and z is distance. z/v is equal to time to contact, which is optically specified by τ (Lee, 1976). v is optically specified by GOFR, which is the angular velocity of texture elements corresponding to the ground plane in a given visual direction (Larish & Flach, 1990). Thus, in terms of optical variables, ideal deceleration is proportional to GOFR/2τ.

[3] Although eye height is an intrinsic unit, seconds (and, hence, eye heights per second squared) are extrinsic units.

recalibration. In Experiment 4, the mapping from brake position to deceleration was manipulated by the introduction of an external force.

Experiment 1

In Experiment 1, I tested the hypothesis that information about ideal deceleration is scaled to maximum deceleration by manipulating brake strength as a between-subjects variable with three levels (weak, medium, and strong). I analyzed trials to identify the onset of individual brake adjustments at the beginning of and throughout the trial. I calculated the ideal deceleration at the onset of each brake adjustment and then scaled it to the maximum deceleration in each condition.

Consider how brake strength should affect the initiation of brake adjustments at the beginning of and throughout the trial. Actors calibrated to the weak brake should initiate positive brake adjustments (i.e., brake adjustments resulting in an increase in deceleration) at lower values of ideal deceleration than actors calibrated to the strong brake. However, if ideal deceleration is perceived in intrinsic units of maximum deceleration, then the ratio of ideal deceleration at the onset of brake adjustments to maximum deceleration should be the same in all three conditions. For example, suppose the mean ideal deceleration at the onset of positive brake adjustments is 2.5 m/s^2 for actors using the weak brake, with a maximum deceleration of 5.0 m/s^2 (i.e., 50% of maximum deceleration). Then the mean ideal deceleration at the onset of positive brake adjustments should be 4.5 m/s^2 for actors using the strong brake with a maximum deceleration of 9.0 m/s^2.

Method

Participants. Thirty undergraduate students (9 women and 21 men; average age 20.9 years) participated in Experiment 1. Ten participants were randomly assigned to each brake strength condition. All but 1 participant had normal or corrected-to-normal vision, and all but 2 had a valid driver's license. The mean number of years of driving experience was 4.8.

Displays and apparatus. Displays were created via OpenGL and generated by a Dell Precision 530 work station equipped with a 1.7 GHz Intel Xeon processor and an nVidia Quadro2 graphics card. Displays were rear projected by a CRT projector onto a large (1.8 m × 1.2 m) screen at a frame rate of 60 Hz. The first 21 participants (7 per group) were run with a Barco Graphics 800 projector at a resolution of 1,024 × 768 pixels. Before the remaining 9 participants were run, the projector was replaced by a new Barco Cine 8 projector capable of generating a higher resolution (1,280 × 1,024 pixels) image. Participants viewed the displays with both eyes under nonstereo conditions from a distance of approximately 1 m. The borders of the projection screen and the surrounding walls were covered with a black felt fabric to reduce the salience of the screen frame. The displays simulated observer movement along a linear path toward three red and white, octagonal stop signs (see Figure 2).[4] The sky was light blue, and there was a gray, cement-textured ground surface 1.1 m below the actor's viewpoint. One stop sign was positioned on the actor's simulated path of motion, and the other two were positioned to the right and left. The radius of the signs varied randomly between 0.25 and 0.50 m on each trial, and the distance between stop signs was always four times the radius. The signs were not anchored to the ground by a post but rather appeared to be floating above the surface, with the center of each stop sign at the same height as the actor's viewpoint. Floating stop signs were originally used to eliminate any static cues to distance. However, subsequent experiments reported in a different article (Fajen, 2005a) have confirmed that performance is unaffected by the presence or absence of posts.

Braking was controlled with a Microsoft Sidewinder Force Feedback 2 joystick. Participants increased deceleration by pulling the joystick from the neutral center position. The brake was programmed so that deceleration was proportional to joystick position. Deceleration ranged from 0 m/s^2 in the neutral center position to the maximum deceleration (5, 7, or 9 m/s^2) in the downmost position. The maximum displacement of the joystick was approximately 10 cm. Joystick position was sampled at a rate of 60 Hz and used to update the display with a loop time of one frame. The joystick was positioned in a comfortable location on a small table in front of the participant and off to the side of his or her preferred hand.

There were five initial times to contact (2.5, 3.0, 3.5, 4.0, and 4.5 s), and five initial distances (28.6, 30.4, 32.1, 33.9, 35.7 m in the weak brake condition; 40.0, 42.5, 45.0, 47.5, 50.0 m in the medium brake condition; and 51.4, 54.6, 57.9, 61.1, 64.3 m in the strong brake condition). It was necessary to use shorter initial distances (which translated to lower initial speeds because initial speed was determined by the combination of initial distance and time to contact) in the weak brake condition to avoid the situation in which it would be impossible to stop in time. Longer initial distances were used in the strong brake condition to avoid the situation in which the initial speed was so slow relative to the maximum deceleration that the actor could stop almost immediately on initiating deceleration. The actual values of initial distance for each brake strength condition were determined so that the initial ideal deceleration expressed as a percentage of maximum deceleration was the same for each combination of initial time to contact and initial distance.

Procedure. Participants sat in an adjustable chair in front of a large (1.8 m × 1.2 m) rear projection screen. The projection screen was located approximately 1 m in front of the participant's viewpoint so that it encompassed 85° of the field of view in the horizontal dimension and 62° in the vertical dimension. Prior to the experiment, the seat was adjusted so that the participant's seated eye height was approximately 1.1 m, which was equal to the simulated eye height. Participants were instructed to use the joystick as a hand-operated brake to stop as closely as possible to the stop signs. Following Yilmaz and Warren (1995), participants were given specific instructions to encourage smooth braking. They were told to imagine that they were driving an actual automobile, in which sudden or jerky brake adjustments would be uncomfortable and unsafe. They were also discouraged from waiting until the last possible moment before initiating maximum deceleration.

Participants initiated trials by moving the joystick to the neutral, zero-deceleration position and pressing the trigger button on the joystick. The scene appeared, and simulated motion toward the stop signs began immediately. Displays ended when participants came to a stop. Even if they collided with the stop sign, the trial continued until speed was equal to zero. To indicate that a collision occurred, an audio signal (a beep) lasting 1 s was played on impact with the stop sign. The final frame was displayed for 1 s before the intertrial screen appeared.

Design. The design for Experiment 1 was 3 (brake strength) × 5 (initial time to contact) × 5 (initial distance). Brake strength was a between-subjects factor, and initial time to contact and distance were within-subject factors. Trials were presented in a completely random order, and there were four repetitions per condition, for a total of 100 trials. Prior to the experiment, participants completed a practice session consisting of 100 trials under the same conditions used in the experiment. Participants were asked to take a short break between the practice and experiment sessions. The entire experiment lasted approximately 30 min.

Data analysis. During each trial, the computer recorded the actor's simulated distance from the target (z), speed (v), and deceleration (d) at a sampling rate of 60 Hz. Final stopping distance was determined by the distance from the actor to the target on the final frame (i.e., when speed

[4] Three stop signs, rather than one, were used to enhance optical expansion at larger distances for which the optical expansion rate was low.

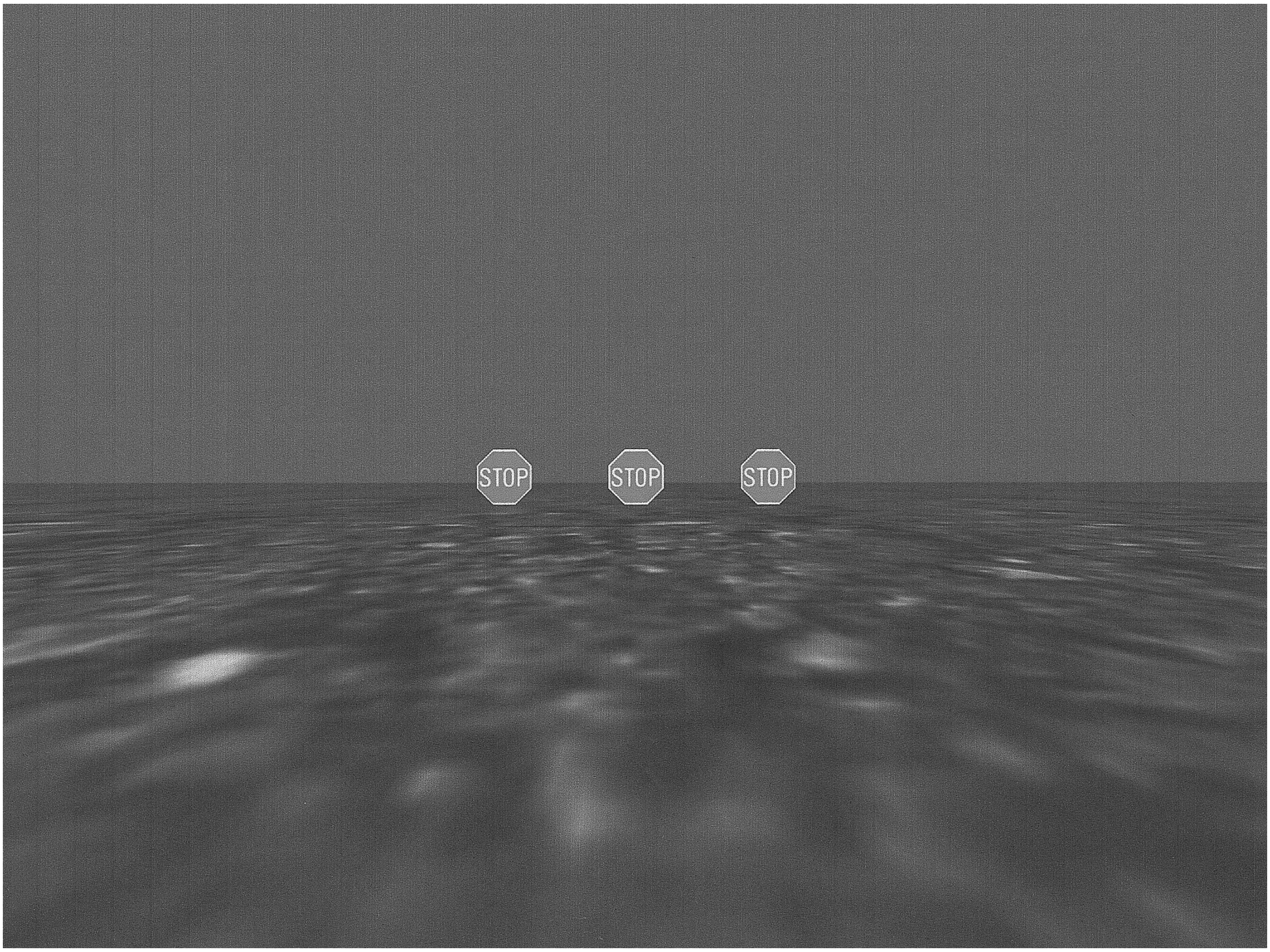

Figure 2. Screenshot of a sample frame from the displays used in all four experiments.

equaled zero), regardless of whether the participant stopped before or crashed into the target.

Individual brake adjustments were identified with a MATLAB program written to find transition points (i.e., starts, stops, and reversals) in the deceleration profile from each trial. It identified the initial brake adjustment by looking for the first window lasting 200 ms (12 frames) over which the brake was adjusted by at least 10% of the maximum deceleration. The program then searched for three types of transition points: starts, stops, and reversals. *Starts* were recorded when the actor increased or decreased deceleration by at least 10% of maximum deceleration over a 200-ms window. Brake adjustments that resulted in changes in deceleration less than 10% of maximum deceleration or that lasted less than 200 ms were not counted. *Stops* were recorded when the actor stopped moving the brake such that deceleration was held constant (plus or minus 1% of maximum deceleration) for at least 200 ms. *Reversals* were recorded when the actor reversed the direction of motion of the brake such that deceleration at the reversal point was at least 5% of maximum deceleration greater than (for an inverted U-shaped reversal) or less than (for a U-shaped reversal) deceleration at the beginning and end of a 200-ms window surrounding the reversal point. After the program searched for starts, stops, and reversals, it identified individual brake adjustments by looking for starts followed by stops or reversals and reversals followed by stops or reversals. In addition to identifying individual brake adjustments, the program also calculated ideal deceleration ($v^2/2z$) at the onset of the initial brake adjustment as well as the onset of each subsequent brake adjustment (i.e., start or reversal).

Results and Discussion

Final stopping distance. Mean final stopping distance as a function of initial time to contact for each brake strength condition is shown in Figure 3. The main effect of initial time to contact, $F(4, 108) = 39.51$, $p < .001$, was significant, but neither the main effect of brake strength, $F(2, 27) = 1.39$, $p = .27$, nor the initial Time to Contact × Brake Strength interaction, $F(8, 108) = 1.19$, $p = .31$, was significant. Thus, overall performance was comparable across the three brake strength conditions.

Ideal deceleration at onset of initial brake adjustment. Figure 4A shows the mean ideal deceleration in extrinsic units (meters per second squared) for all three brake strength conditions. As expected, brake strength affected the ideal deceleration at the onset of braking, $F(2, 27) = 58.85$, $p < .001$. However, when ideal deceleration was expressed in intrinsic units (as a percentage of maximum deceleration), the differences among brake strength conditions disappeared, $F(2, 27) = 1.44$, $p = .26$ (see Figure 4B).

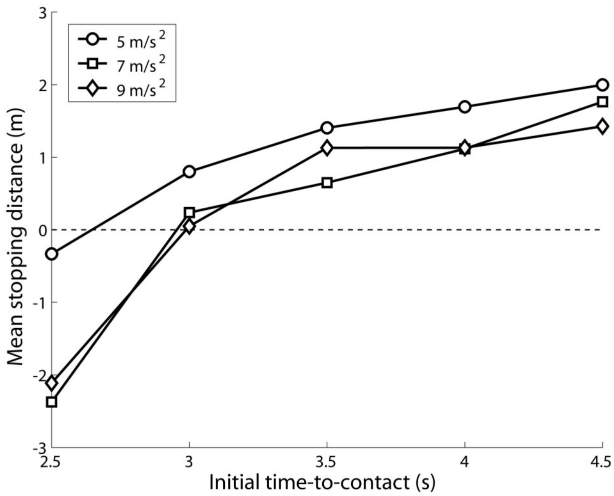

Figure 3. Mean final stopping distance (in meters) as a function of initial time to contact (in seconds) for the weak, medium, and strong brake conditions in Experiment 1. A negative stopping distance indicates that the observer stopped after colliding with the sign. m/s^2 = meters per second squared.

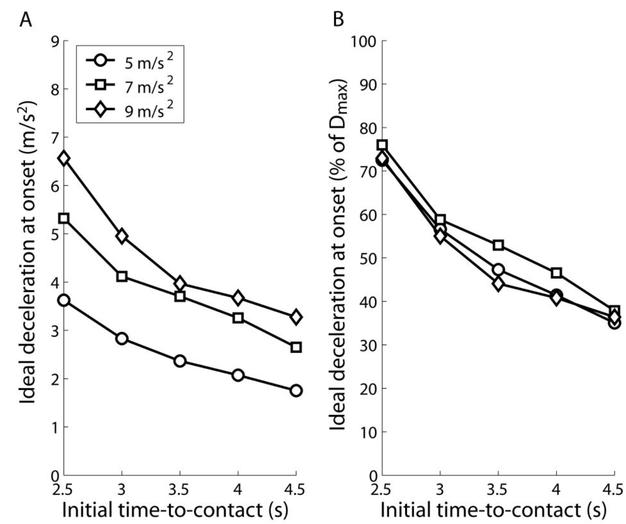

Figure 5. Mean ideal deceleration at the onset of the initial brake adjustment (A) in extrinsic units (meters per second squared) and (B) in intrinsic units (percentage of maximum deceleration) as a function of initial time to contact (in seconds) for all three brake strength conditions in Experiment 1. D_{max} = maximum deceleration.

Figure 5 shows the same data broken down by initial time to contact. In extrinsic units, the main effect of initial time to contact, $F(4, 108) = 216.99$, $p < .001$, and the initial Time to Contact × Brake Strength interaction, $F(8, 108) = 6.94$, $p = .001$, were significant (see Figure 5A). In intrinsic units, the main effect of initial time to contact was significant, $F(4, 108) = 249.17$, $p < .001$, but the interaction was not ($F < 1$; see Figure 5B).

The main effect of initial time to contact was probably due to the fact that ideal deceleration at the beginning of the trial was higher and increased more rapidly when initial time to contact was shorter. As long as the initial brake adjustment is large enough and executed quickly enough to keep the ideal deceleration from exceeding maximum deceleration, then it does not matter when braking is initiated. In practice, the onset of braking is likely to be affected by a variety of factors, such as initial time to contact, distance, and speed as well as the costs associated with approach time and collision. Thus, just as braking is not initiated at a fixed value of τ (as Lee, 1976, originally proposed, but Yilmaz & Warren, 1995, refuted), neither does it appear to be initiated at a fixed value of perceived ideal deceleration. Given the flexibility necessary to control braking across changing conditions and costs, it seems unlikely that deceleration is triggered at a margin value of any optical variable.

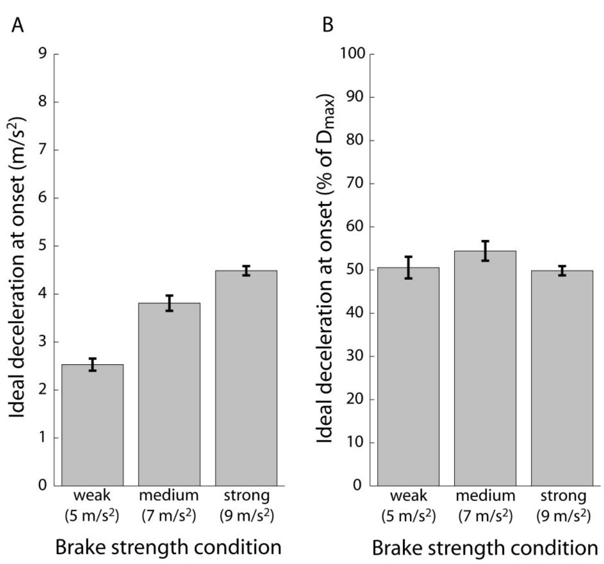

Figure 4. Mean ideal deceleration at the onset of the initial brake adjustment (A) in extrinsic units (meters per second squared) and (B) in intrinsic units (percentage of maximum deceleration) for all three brake strength conditions in Experiment 1. Error bars indicate ±1 standard error. D_{max} = maximum deceleration.

Ideal deceleration at onset of subsequent brake adjustments. A similar pattern of results was observed for subsequent brake adjustments. Separate analyses were run for brake adjustments resulting in a positive change in deceleration and those resulting in a negative change. When ideal deceleration was expressed in extrinsic units (Figure 6A), the effect of brake strength was significant for both positive adjustments, $F(2, 27) = 14.96$, $p < .001$, and negative adjustments, $F(2, 26) = 7.02$, $p < .01$.[5] When ideal deceleration was expressed as a percentage of maximum deceleration (see Figure 6B), the effect of brake strength was not significant ($F < 1$) for either positive or negative adjustments. On average, positive brake adjustments were initiated when ideal deceleration was approximately 50%–55% of maximum deceleration, and negative brake adjustments were initiated when ideal

[5] Data from 1 participant were eliminated from the second analysis because there were too few negative brake adjustments to calculate a reliable estimate of required deceleration at onset.

deceleration was approximately 20%–25% of maximum deceleration.

Percentage of increases as a function of ideal deceleration. Another way of showing that information about ideal deceleration was scaled to maximum deceleration is to plot the percentage of adjustments that resulted in an increase in deceleration as a function of ideal deceleration at the onset of adjustment, expressed in both extrinsic (see Figure 7A) and intrinsic (see Figure 7B) units. To find the critical value of ideal deceleration in each condition, I performed a z transformation of the percentage of positive adjustments and ran a linear regression on ideal deceleration. The value of ideal deceleration at which the regression line crossed 50% positive adjustments was interpreted as the critical value. When ideal deceleration was expressed in meters per second squared, the critical values differed for each brake strength condition, $F(2, 24) = 10.11$, $p < .001$ ($M = 1.5$, 2.0, and 3.1 m/s^2 for the weak, medium, and strong brake conditions, respectively).[6] In units of maximum deceleration, however, there was no statistically significant difference among brake strength conditions ($F < 1$; $M =$ 30.0%, 31.9%, and 32.50%, respectively).

The results of Experiment 1 are consistent with the hypothesis that participants calibrate to different brake strengths by scaling information about ideal deceleration in units of maximum deceleration. Analyses of the onset of initial and subsequent brake adjustments revealed that the ideal deceleration (in extrinsic units of meters per second squared) at which braking was initiated was affected by brake strength. When ideal deceleration was expressed in intrinsic units (i.e., as a percentage of maximum deceleration), the ideal deceleration at onset was the same in all three conditions. In addition, the critical value of ideal deceleration (in intrinsic units) at which 50% of the brake adjustments were positive was also the same across groups.

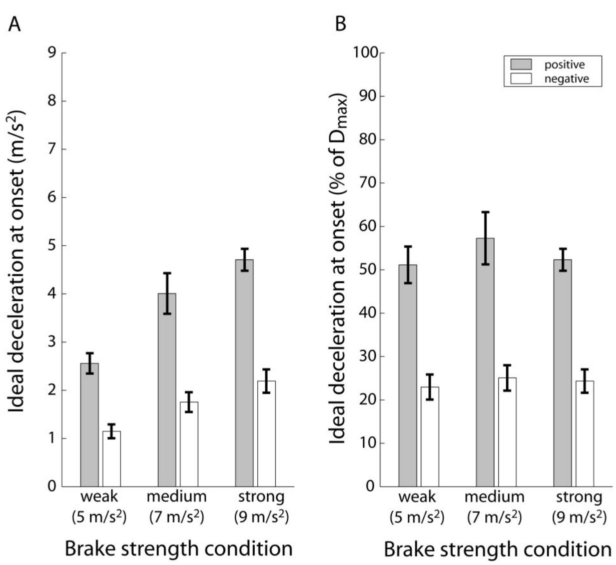

Figure 6. Mean ideal deceleration at the onset of subsequent brake adjustments resulting in a positive change in deceleration (solid bars) and a negative change in deceleration (open bars) for all three brake strength conditions in Experiment 1. A: Ideal deceleration is expressed in extrinsic units (meters per second squared) and B: in intrinsic units (percentage of maximum deceleration). Error bars indicate ±1 standard error. D_{max} = maximum deceleration.

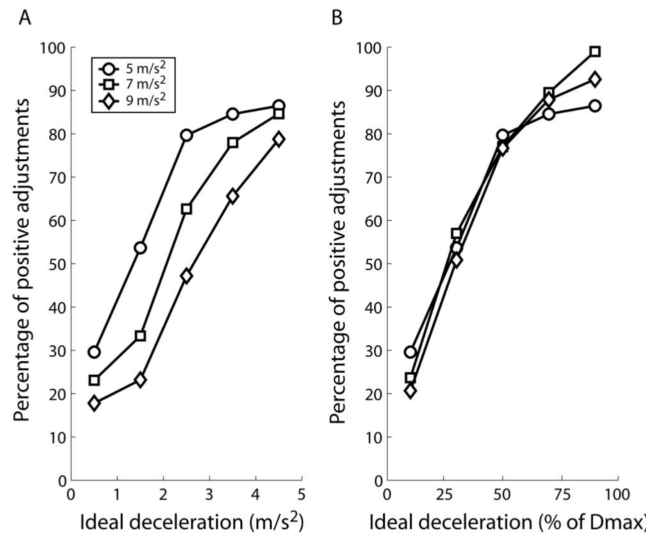

Figure 7. Percentage of positive brake adjustments as a function of ideal deceleration at the onset of adjustment, expressed in both extrinsic (A) and intrinsic (B) units in Experiment 1. m/s^2 = meters per second squared; D_{max} = maximum deceleration.

Experiment 2

Experiment 1 demonstrated that actors are able to calibrate to brakes with different strengths after practice, in theory by adjusting the scale in which information about ideal deceleration is detected. However, the design of Experiment 1 did not permit investigation of the rate at which participants calibrated to brake strength. In Experiment 2, trials were presented in blocks of 25, and the same analyses used in Experiment 1 were performed on the data from each block. In the first four blocks, brake strength was manipulated as a between-subjects factor with three levels (5.0 m/s^2 for Group A, 7.0 m/s^2 for Group B, and 9.0 m/s^2 for Group C). On the last six blocks, brake strength was the same (7.0 m/s^2) for all three groups. To determine the rate of calibration during the first four blocks and the rate of recalibration following the change in brake strength in Block 5, I calculated the mean ideal deceleration at the onset of brake adjustments in both extrinsic (meters per second squared) and intrinsic (percentage of maximum deceleration) units. Following from Experiment 1, participants were considered to be fully calibrated when the mean ideal deceleration in intrinsic units was the same for all three groups.

The other goal of Experiment 2 is to rule out a possible confound in Experiment 1. Recall that I normalized the initial conditions across groups in Experiment 1 by varying the range of initial distances so that the ratio of initial ideal decelerations to maximum deceleration was the same for all three groups. If participants initiated braking at the same time after the beginning of the trial,

[6] Data from 5 participants were excluded from this analysis because there were too few brake adjustments to calculate a reliable estimate of the percentage of positive adjustments in each required deceleration bin.

then because the range of initial ideal decelerations was normalized across groups, the mean ideal deceleration at braking onset would be the same percentage of maximum deceleration for all three groups.[7] In other words, a simple strategy of initiating braking at a fixed time after the beginning of the trial would yield the same results regardless of whether the participants in each condition were actually calibrated to the strength of the brake.

One way to rule out this possible confound is to conduct additional analyses of brake adjustment magnitude. If participants in all three groups are calibrated to the same brake strength (e.g., 7 m/s^2) rather than to the actual brake strength (e.g., 5, 7, or 9 m/s^2), then displacing the brake by an amount equal to the perceived ideal deceleration would result in a tendency to undershoot when the actual brake is weaker and overshoot when the actual brake is stronger.[8] Conversely, if participants are calibrated to brake strength in each condition, then there should be no differences in the degree of undershoot or overshoot.

Another way to rule out the above interpretation of Experiment 1 is to manipulate the initial conditions independently of brake strength. In Experiment 2, the range of initial ideal decelerations was normalized to brake strength during the first four blocks as it was in Experiment 1. However, when brake strength was changed to 7 m/s^2 on the fifth block of Experiment 2, the range of initial ideal decelerations stayed the same for each group. If participants adopt a simple strategy of initiating deceleration at the same time after the beginning of the trial, then the change in brake strength on Block 5 should not affect the mean ideal deceleration at braking onset. That is, participants in Group A should continue to initiate braking at lower levels of ideal deceleration than participants in Group C. However, if the invariance in Experiment 1 resulted from calibration of information to action, then in Experiment 2, participants in all three groups should initiate braking at the same level of ideal deceleration following recalibration to the change in brake strength on Block 5.

Method

Participants. Thirty undergraduate students (9 women and 21 men; average age 19.7 years) participated in Experiment 2. Ten participants were randomly assigned to each condition. All participants had normal or corrected-to-normal vision and a valid driver's license. The mean number of years of driving experience was 3.5.

Displays and apparatus. Trials were presented in 10 blocks of 25. Within each block, there were five levels of initial time to contact (2.5, 3.0, 3.5, 4.0, and 4.5 s) and five levels of initial distance (28.6, 30.4, 32.1, 33.9, 35.7 m for Group A; 40.0, 42.5, 45.0, 47.5, 50.0 m for Group B; and 51.4, 54.6, 57.9, 61.1, 64.3 m for Group C). On the first 4 blocks, brake strength varied among groups (5.0, 7.0, and 9.0 m/s^2 for Groups A, B, and C, respectively). On the last 6 blocks, brake strength was 7.0 m/s^2 for all three groups. Participants were not informed that brake strength changed during the experiment. The displays and apparatus were otherwise the same as those used in Experiment 1.

Procedure. The same procedure that was used in Experiment 1 was used in Experiment 2.

Design. The design for Experiment 2 was 3 (group) × 10 (block) × 5 (initial distance) × 5 (initial time to contact). Group was a between-subjects factor, and block, initial distance, and initial time to contact were within-subject factors. There were 25 trials per block and 10 blocks for a total of 250 trials. Unlike Experiment 1, participants did not practice before the experiment. The experiment lasted approximately 45 min.

Data analysis. Individual brake adjustments were identified in the deceleration time series from each trial according to the same procedure used in Experiment 1. I measured the magnitude of each brake adjustment by taking the difference between the deceleration at the beginning and at the end of the adjustment and then dividing by the difference between the current and ideal deceleration at the beginning of the adjustment. For example, if the ideal deceleration was 2.5 m/s^2 and the participant increased deceleration from 1.5 m/s^2 to 3.0 m/s^2, then the scaled magnitude of adjustment would be 1.5/1.0 = 1.50. This means that the participant overshot ideal deceleration by 50%.

Results and Discussion

On the basis of the analysis of initial brake adjustments, participants calibrated almost immediately. The mean ideal deceleration (in extrinsic units) at the onset of initial braking was significantly ($p < .05$) different across groups in each of the first four blocks (see Figure 8A). That is, participants in Groups A and C initiated braking at lower (Group A) and higher (Group C) levels of ideal deceleration compared with those in Group B. In intrinsic units, ideal deceleration at braking onset was not statistically different across groups during any of the first four blocks (see Figure 8B). Thus, it appears that participants completely calibrated to the strength of the brake in fewer (possibly far fewer) than 25 trials.

If the invariance in Blocks 1 through 4 (and in Experiment 1) was due to normalization of the initial conditions rather than to calibration of information to action, then one would expect a tendency to undershoot in Group A and a tendency to overshoot in Group C. Figure 9 shows the mean scaled magnitude of initial brake adjustments as a function of block for all three groups. There was a tendency to overshoot in all three groups, which has been reported in previous experiments (e.g., Fajen, 2005a) and most likely reflects a bias to avoid collisions. More important, there were no significant differences ($p < .05$) among groups in the degree of overshoot during Blocks 1 through 4. Thus, the analysis of brake adjustment magnitude suggests that the invariance in ideal deceleration at onset was due to calibration rather than to normalization of the initial conditions.

Second, if the invariance in ideal deceleration at onset was due to the initial conditions rather than to calibration, then participants in Groups A and C should continue to initiate braking at lower and higher (respectively) levels of ideal deceleration compared with Group B even after brake strength changes on Block 5. As shown in Figure 8A, however, participants in Group A began to initiate braking at higher values of ideal deceleration after brake strength

[7] To illustrate this point, suppose initial time to contact is 3.5 s and initial distance is normalized to brake strength: 32.1 m for Group A (5 m/s^2), 45.0 m for Group B (7 m/s^2), and 57.9 m for Group C (9 m/s^2). If braking was initiated 1.5 s into the trial, then the ideal deceleration at braking onset would be different in extrinsic units (2.30, 3.21, and 4.14 m/s^2 for Groups A, B, and C, respectively) but the same in intrinsic units (46% of maximum deceleration).

[8] Given the example in Footnote 6, perceived ideal deceleration at 1.5 s would be 33% for Group A, 46% for Group B, and 59% for Group C. Displacing the brake by an amount equal to the perceived ideal deceleration would result in a current deceleration of 1.65, 3.21, and 5.31 m/s^2, respectively. If one compares current deceleration with ideal deceleration at 1.5 s (i.e., 2.30, 3.21, and 4.14 m/s^2) for each group, there should be a tendency to undershoot in Group A and overshoot in Group C.

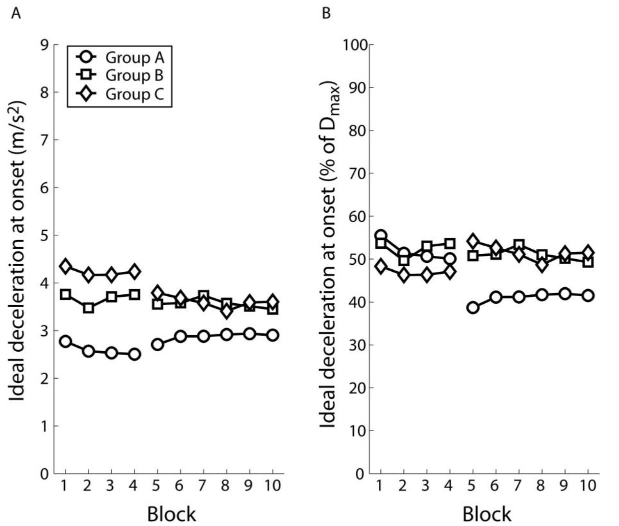

Figure 8. Mean ideal deceleration at the onset of the initial brake adjustment (A) in extrinsic units (meters per second squared) and (B) in intrinsic units (percentage of maximum deceleration) as a function of block for all three groups in Experiment 2. D_{max} = maximum deceleration.

increased from 5 to 7 m/s^2, and those in Group C began to initiate braking at lower values of ideal deceleration after brake strength decreased from 9 to 7 m/s^2. To test whether these changes in ideal deceleration at onset were significant, I compared the data from Blocks 4 and 10. A 3 (group) × 2 (block) analysis of variance (ANOVA) revealed a significant interaction, $F(2, 27) = 10.65$, $p < .001$, with a significant simple main effect of block in Groups A, $F(1, 9) = 36.96$, $p < .001$, and C, $F(1, 9) = 10.64$, $p < .01$. Because the range of initial distances within each group was the same throughout all 10 blocks, these findings rule out the possibility that the invariance observed in Experiment 1 and in the first four blocks of Experiment 2 was attributable to a simple strategy of initiating braking at the same time after the beginning of the trial.

Although participants in Groups A and C clearly recalibrated to the change in brake strength on Block 5, those in Group A continued to initiate braking at slightly lower values of ideal deceleration (see Figure 8). Thus, it appears that the range of initial conditions had some residual effect on braking initiation for participants in Group A but not for those in Group C. This asymmetry is most likely because of differences in the consequences of switching to a weaker brake compared with those of switching to a stronger brake. When participants in Group C switched from a strong brake to a medium strength brake, they quickly learned that it was necessary to initiate deceleration earlier to avoid a collision. In contrast, when those in Group A switched from a weak brake to a medium strength brake, it was less important to initiate braking later because the consequences of initiating braking too early are less severe than the consequences of initiating braking too late. Does this mean that participants in Group A failed to completely recalibrate after brake strength changed in Block 5? If so, then there should be a bias to overshoot after the change in brake strength. Indeed, there was a weak but statistically significant ($p <$ .05) tendency to overshoot on the fifth and sixth blocks (see Figure 9). However, this overshoot bias diminished and failed to reach significance in Blocks 7 through 10, suggesting that participants in Group A eventually recalibrated.

Further evidence that Group A eventually recalibrated is provided by the analysis of subsequent brake adjustments, which are less affected by the initial conditions. Because there were not enough data to obtain a reliable estimate of ideal deceleration at the onset of subsequent brake adjustments for each block, the data were pooled across the last six blocks. A one-way ANOVA of the effect of group was not significant, $F(2, 27) = 1.27$, $p = .30$ ($M \pm SD = 3.50 \pm 0.72$, 4.08 ± 1.04, and 3.58 ± 0.86, for Groups A, B, and C, respectively). Thus, the failure of participants in Group A to initiate braking at higher values of ideal deceleration after brake strength changed was the result of a tendency to initiate braking early in the trial rather than to a failure to recalibrate.

In summary, the results of Experiment 2 indicate that participants are capable of calibrating to the strength of the brake and recalibrating to changes in brake strength within fewer than 25 trials. The aim of Experiment 3 is to provide a more stringent test of rapid recalibration by manipulating brake strength on each trial. Experiment 2 also confirms that the invariance observed in Experiment 1 was not due to the range of initial conditions. Although the initial conditions might have affected the ideal deceleration at the onset of braking, they did not affect brake adjustment magnitude, nor did they affect the initiation of subsequent brake adjustments. Thus, it can be concluded that the invariance observed in Experiments 1 and 2 resulted from calibration—that is, the scaling of information to one's action capabilities.

Experiment 3

In the real world, maximum deceleration can be affected by a variety of factors (e.g., load, surface friction, surface slope) other than brake strength. Some of these factors can change quickly, which suggests that actors must be able to rapidly recalibrate to control braking across a variety of real-world conditions. Within the framework introduced above, recalibration involves rescaling information about ideal deceleration so that it is still possible to stop safely with the new brake whenever the ideal deceleration

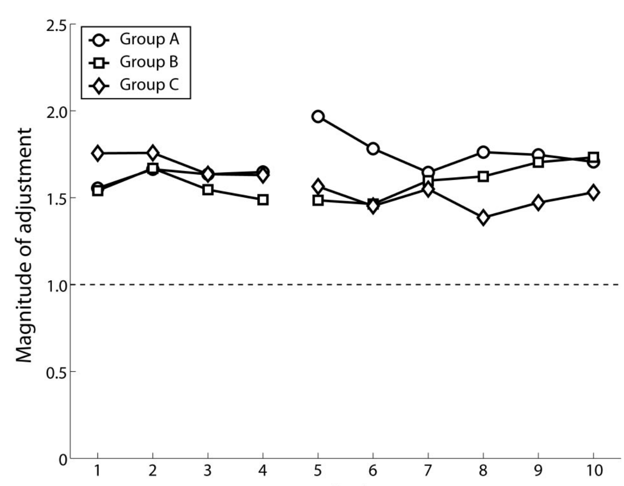

Figure 9. Mean magnitude of initial brake adjustment as a function of block for all three groups in Experiment 2.

measures less than 1.0. How do actors discover the right metric for detecting information about ideal deceleration? Although there is no information in optic flow about maximum deceleration per se, the optical consequences of individual brake adjustments can be used to calibrate information to maximum deceleration. If the actor is properly calibrated, then the ideal deceleration (expressed as a percentage of maximum deceleration) will always drift away from brake position (expressed as a percentage of maximum brake position). This is illustrated in Figure 1C. Ideal deceleration drifts upward when brake position (or current deceleration) is less than ideal deceleration and downward when brake position is greater than ideal deceleration. If perceived ideal deceleration drifts toward brake position, then the actor is not properly calibrated. A rather unsettling example of this can occur the first time a driver tests out the brakes after hitching a heavy trailer. The driver may perceive that there is still time to stop (i.e., that ideal deceleration is less than 100% of maximum deceleration). However, if the additional load is large enough to significantly affect maximum deceleration, then perceived ideal deceleration may continue to increase even when maximum deceleration is applied. The upward drift in perceived ideal deceleration indicates that the units in which ideal deceleration is perceived are too large (i.e., that the driver is calibrated to a stronger brake) and must be adjusted. To recalibrate to the new brake strength, the driver would have to decrease the metric until perceived ideal deceleration always drifted away from brake position.[9]

The example above illustrates that the information necessary to recalibrate is, in principle, available in the optical consequences of a single brake adjustment. However, it may take more (perhaps many more) than one brake adjustment to completely recalibrate. The purpose of Experiment 3 is to investigate the rate of recalibration by manipulating brake strength as a randomly presented within-subject variable. To the extent that participants are able to recalibrate on the basis of the initial brake adjustment, one would expect to find evidence of recalibration (similar to that in Experiments 1 and 2) in subsequent brake adjustments on the same trial.

Method

Participants. Twelve undergraduate students (6 women and 6 men; average age 18.8 years) participated in Experiment 3. All participants had normal or corrected-to-normal vision, and all but 1 had a valid driver's license. The mean number of years of driving experience was 2.67. Data from 1 participant were excluded from all analyses because of the failure to follow instructions.

Displays and apparatus. Displays were similar to those used in Experiments 1 and 2, with a couple of exceptions. First, there was only one group of participants, and brake strength was manipulated as a randomly presented within-subject variable with three levels (5.0, 7.0, and 9.0 m/s^2). Second, there was only one set of initial distances (40.0, 42.5, 45.0, 47.5, and 50.0 m). The same values of initial time to contact used previously were used in Experiment 3.

Procedure. The procedure was the same. Participants were not told that brake strength was manipulated.

Design. The design for Experiment 3 was 3 (brake strength) $\times$ 5 (initial distance) $\times$ 5 (initial time to contact). All three variables were within-subject, and trials were presented in a completely random order. There were four repetitions per condition, for a total of 300 trials. Prior to the experiment, participants completed a practice session consisting of 100 trials with brake strength set to 7.0 m/s^2. Participants were asked to take a short break after the practice session and after the 100th and 200th trials of the experiment. The entire experiment lasted approximately 1 hr.

Results and Discussion

Initial brake adjustments. Braking was initiated at approximately the same value of ideal deceleration in all three brake strength conditions (M = 3.49, 3.40, and 3.33 m/s^2), which was unsurprising because there is no information about the strength of the brake prior to the onset of braking. There was a general tendency to overshoot on the initial brake adjustment (which probably reflects a safety bias to brake too hard rather than not hard enough), but the tendency to overshoot was magnified in the medium and strong brake conditions, $F(2, 20) = 18.77$, $p < .001$ (see Figure 10). This was also expected because the same brake displacement resulted in a larger change in deceleration when the brake was stronger. Thus, the effect of the initial brake adjustment on the rising ideal deceleration at the beginning of each trial tended to be smaller in the weak brake condition than in the strong brake condition. The question is whether participants were able to notice these differences in the optical consequences of initial brake adjustments and adapt their braking behavior accordingly on subsequent brake adjustments executed during the same trial.

Subsequent brake adjustments. If participants were able to recalibrate, then the effect of brake strength on the magnitude of subsequent positive brake adjustments should be weaker than it was for the initial brake adjustment. However, the magnitude of subsequent positive brake adjustments was also significantly affected by brake strength, $F(2, 20) = 42.77$, $p < .001$ (see Figure 10), and the difference between the magnitude of initial and subsequent brake adjustments was not significant ($F < 1$). Therefore, analysis of the magnitude of brake adjustments failed to provide any evidence of rapid, single-brake-adjustment recalibration.

Percentage of increases as a function of ideal deceleration. Another test of recalibration is the effect of brake strength on the likelihood of making a positive brake adjustment. Recall that participants who were calibrated to the weak brake in Experiment 1 made positive brake adjustments at smaller values of ideal deceleration (in meters per second squared) than participants in the stronger brake conditions. If participants in Experiment 3 were able to recalibrate (at least partially) on the basis of the initial brake adjustment, then the likelihood of making a positive brake adjustment should be greater in the weak brake condition and smaller in the strong brake condition. Figure 11 shows the mean percentage of subsequent brake adjustments that resulted in an increase in deceleration as a function of ideal deceleration at the onset of braking. Using the same method that was used in Experiment 1, I calculated the critical value of ideal deceleration at which 50% of the brake adjustments were positive for each par-

[9] Note that if the brake is linear, then the actor does not have to perform emergency stops to test out the maximum limits. The direction of drift in perceived ideal deceleration relative to brake position specifies whether the actor is calibrated regardless of brake position. It may, however, help to test out the maximum limits because there is no uncertainty about brake position when the brake is in the maximum position. For positions in between zero and maximum, uncertainty about brake position could complicate attempts to calibrate.

ticipant.[10] The mean critical value was significantly smaller in the weak brake condition, $F(2, 14) = 22.52$, $p < .001$ ($M = 1.79$, 2.37, and 2.34). However, the differences among critical values were considerably smaller than in Experiment 1, and there was no difference between the medium and strong brake conditions. Therefore, at most, participants partially recalibrated when the brake was weaker.

Taken together, the analyses of subsequent brake adjustments provide very little evidence that participants were able to rapidly recalibrate on the basis of the optical consequences of the initial brake adjustment. It is not surprising that the manipulation of brake strength had a significant effect on final stopping distance, $F(2, 20) = 79.80$, $p < .001$, as participants were more likely to stop closer to the stop sign or collide in the weak brake condition and were more likely to stop farther in front of the sign in the strong brake condition. The Brake Strength $\times$ Initial Time to Contact interaction indicated that the effect of brake strength was magnified at small initial time-to-contact values, $F(8, 80) = 45.97$, $p < .001$ (see Figure 12). Thus, although there is sufficient information to recalibrate in the optical consequences of a single brake adjustment, recalibration appears to take more than one brake adjustment.

Although participants were unable to recalibrate on the basis of the initial brake adjustment, the optical consequences of each subsequent adjustment (i.e., following the initial adjustment on the same trial) provided additional information that could be also used to recalibrate. Perhaps participants were unable to recalibrate on the basis of the initial adjustment alone, but the initial adjustment together with all of the subsequent adjustments on the same trial were sufficient for partial recalibration. I conducted a post hoc analysis to determine whether braking was influenced by the strength of the brake on the previous trial. If participants are able to recalibrate on the basis of all of the brake adjustments made during the previous trial, then they should initiate braking earlier when brake strength on the previous trial was weak and later when brake strength on the previous trial was strong. Figures 13A and 14A show the mean ideal deceleration at the onset of initial and subsequent brake adjustments as a function of brake strength on the previous trial. Indeed, participants did initiate brake adjustments at lower values of ideal deceleration when brake strength was weak on the previous trial and higher values of ideal deceleration when brake strength was strong the on the previous trial, $F(2, 20) = 17.50$, $p < .001$, for the initial brake adjustment; $F(2, 20) = 10.57$, $p < .01$, for positive subsequent adjustments; $F(2, 20) = 1.58$, $p = .23$, for negative subsequent adjustments. Although participants partially recalibrated, they did not fully recalibrate. Figures 13B and 14B show the same data with ideal deceleration expressed as a percentage of maximum deceleration on the previous trial. If participants fully calibrated to the strength of the brake on the previous trial, then ideal deceleration at onset should be unaffected by brake strength when expressed as a percentage of maximum deceleration on the previous trial. However, statistical analyses confirmed a main effect of brake strength for initial, $F(2, 20) = 198.52$, $p < .001$, positive subsequent, $F(2, 20) = 19.87$, $p < .01$, and negative subsequent, $F(2, 20) = 16.10$, $p < .01$, adjustments. Taken together, the results suggest that participants were unable to recalibrate on the basis of the initial brake adjustment alone but that the additional adjustments executed during the same trial provided sufficient information for partial recalibration.

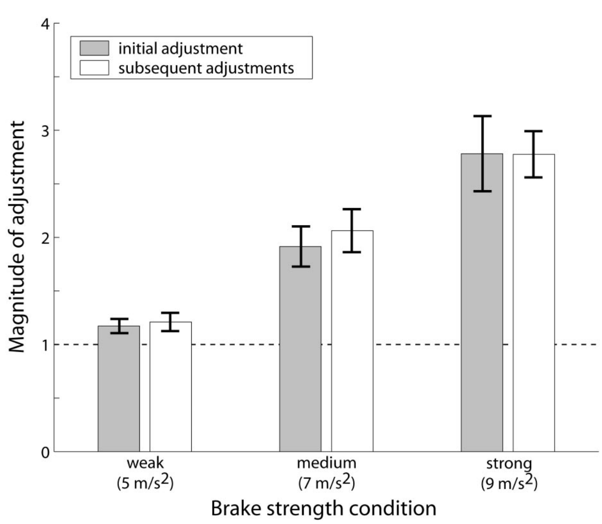

Figure 10. Mean magnitude of initial (solid bars) and subsequent brake adjustments (open bars) for all three brake strength conditions in Experiment 3. Error bars indicate ±1 standard error. m/s^2 = meters per second squared.

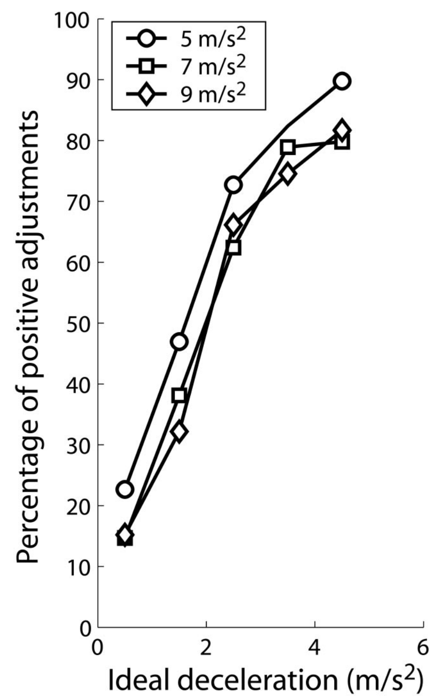

Figure 11. Percentage of positive adjustments as a function of ideal deceleration at the onset of adjustment for Experiment 3. m/s^2 = meters per second squared.

[10] Data from 3 of the remaining 11 participants were excluded from this analysis because there were too few brake adjustments to calculate a reliable estimate of the percentage of positive adjustments in each required deceleration bin.

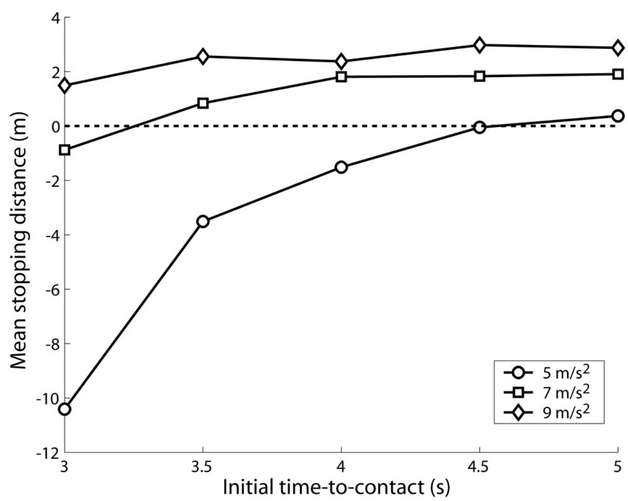

Figure 12. Mean final stopping distance (in meters) as a function of initial time to contact (in seconds) for the weak, medium, and strong brake conditions in Experiment 3. A negative stopping distance indicates that the observer stopped after colliding with the sign.

If actors are unable to completely recalibrate on the basis of a single brake adjustment and environmental conditions that affect maximum deceleration can change quickly, then how do people avoid collisions in the real world when effective maximum deceleration changes? A conservative strategy is to calibrate to a level of deceleration that is at the low end of the range of maximum decelerations experienced by the actor. In practice, actors may calibrate to the level of deceleration that feels safe and comfortable on the basis of vestibular feedback, which for most of us is well below the actual maximum level of deceleration. This might result

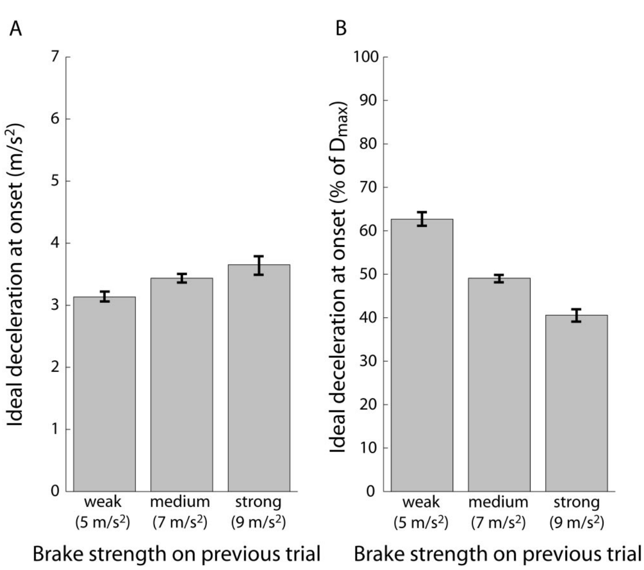

Figure 13. Mean ideal deceleration at the onset of the initial brake adjustment (A) in extrinsic units (meters per second squared) and (B) in intrinsic units (percentage of maximum deceleration) as a function of brake strength on the previous trial in Experiment 3. Error bars indicate ±1 standard error. D_{max} = maximum deceleration.

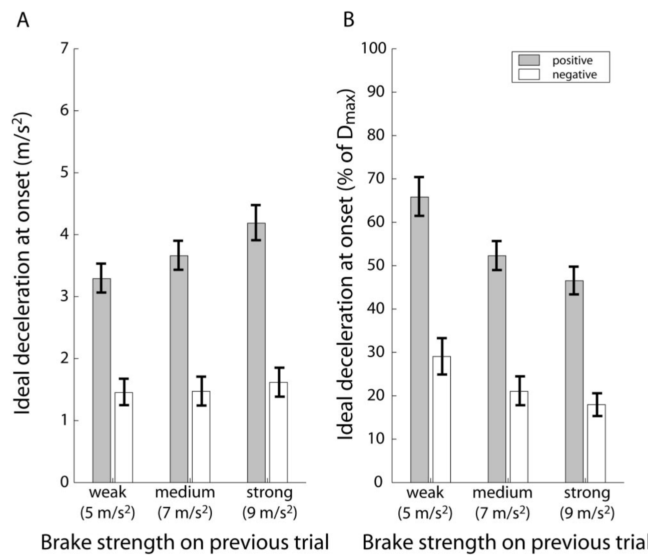

Figure 14. Mean ideal deceleration at the onset of subsequent brake adjustments resulting in a positive change in deceleration (solid bars) and a negative change in deceleration (open bars) as a function of brake strength on the previous trial in Experiment 3. A: Ideal deceleration is expressed in extrinsic units (meters per second squared) and B: in intrinsic units (percentage of maximum deceleration). Error bars indicate ±1 standard error. D_{max} = maximum deceleration.

in longer approach times when the effective maximum deceleration is raised by local conditions (e.g., a strong headwind), but the likelihood of colliding even when the effective maximum deceleration suddenly drops (e.g., because of poor traction) would be considerably lower.

Experiment 4

Perceiving ideal deceleration in units of maximum deceleration can greatly simplify the control of braking because it puts information and control in the same units. Just as ideal deceleration can be expressed as a percentage of maximum deceleration, brake displacement can also be expressed as a percentage of maximum brake displacement. If the brake is designed so that the mapping from brake displacement to deceleration is proportional, then intrinsically scaled information about ideal deceleration specifies the range of brake positions necessary to keep the ideal deceleration within the safe region without the need for knowledge of controller dynamics. For example, if ideal deceleration is 40% of maximum deceleration and perceived as such by a calibrated actor, then the ideal deceleration could be kept within the safe region by the application of 40% or more of maximum deceleration.

In Experiment 4, I manipulated the mapping from brake position to deceleration on each trial by adding a positive or negative external force, similar to introducing a headwind or tailwind. In the negative (-0.5 m/s^2) external force condition, the actor gradually slowed down rather than maintaining a constant speed when the brake was in the neutral position. In the downmost position, there was slightly more deceleration than there was when no external force was present. In this condition, displacing the brake halfway resulted in more deceleration than in the condition without external force. Therefore, analyses of the magnitude of brake adjustments should reveal that actors were more likely to overshoot when increasing deceleration and undershoot when decreasing deceleration. In the positive (0.5 m/s^2) external force condition, the actor gradually accelerated when the brake was in the neutral position and decelerated less when the brake was in the downmost position. Displacing the brake halfway also yielded less deceleration and therefore should result in a tendency to undershoot when increasing the brake and overshoot when decreasing the brake.

Method

Participants. Ten undergraduate students (4 women and 6 men) participated in Experiment 4. The average age was 20.6 years, and all but 1 participant had normal or corrected-to-normal vision. All participants had a valid driver's license, and the mean number of years of driving experience was 4.3.

Displays and apparatus. There were three levels of external deceleration (−0.5, 0.0, and 0.5 m/s^2), five initial distances (40.0, 42.5, 45.0, 47.5, and 50.0 m), and five initial times to contact (3.0, 3.5, 4.0, 4.5, 5.0 s). Deceleration due to braking alone (i.e., disregarding external deceleration) ranged from 0 m/s^2 in the neutral center position to 7 m/s^2 in the downmost position.

Procedure. The procedures were identical to those used in the previous experiments.

Design. The design for Experiment 4 was 3 (external deceleration) × 5 (initial distance) × 5 (initial time to contact), with all variables within subject. Trials were presented in a completely random order, and there were four repetitions per condition, for a total of 300 trials. Prior to the experiment, participants completed a practice session consisting of 100 trials without external deceleration. Participants were asked to take a short break after the practice session and after the 100th and 200th trials of the experimental session. The entire experiment lasted approximately 1 hr.

Results and Discussion

Final stopping distance. Mean final stopping distance as a function of initial time to contact for each condition of external deceleration is plotted in Figure 15. The main effects of external deceleration, $F(2, 18) = 15.56$, $p < .001$, and initial time to contact, $F(4, 36) = 5.33$, $p < .01$, as well as the External Deceleration × Initial Time to Contact interaction, $F(8, 72) = 3.36$, $p < .01$, were all significant.

Magnitude of initial and subsequent brake adjustments. The effect of external deceleration on the magnitude of initial brake adjustments was significant, $F(2, 18) = 24.50$, $p < .001$ (see Figure 16A). Participants overshot the ideal deceleration in all three conditions, but the degree of overshoot was larger in the −0.5 m/s^2 condition than in the 0.0 or 0.5 m/s^2 conditions. The pattern of results for subsequent positive brake adjustments was similar, $F(2, 18) = 41.88$, $p < .001$ (see gray bars in Figure 16B). For subsequent negative adjustments, the pattern of results was opposite, $F(2, 18) = 22.53$, $p < .001$ (see white bars in Figure 16B), as expected.

The results further elucidate the mechanisms by which actors make brake adjustments to keep the ideal deceleration within the safe region. When the brake is designed so that the mapping from brake position to deceleration is proportional, information about ideal deceleration in units of maximum deceleration specifies not only the range of deceleration values but also the range of brake positions necessary to keep the ideal deceleration within the safe region. Thus, knowledge of the mapping from brake position to deceleration (i.e., the controller dynamics) is unnecessary as long as the controller is linear. An interesting question for future research is how brake position is adjusted when the controller dynamics are nonlinear. As long as the minimum and maximum ideal decelerations are mapped to the minimum and maximum brake positions, people should be able to keep ideal deceleration within the safe region. However, there may be a tendency to overshoot or undershoot for ideal decelerations in the middle of the range.

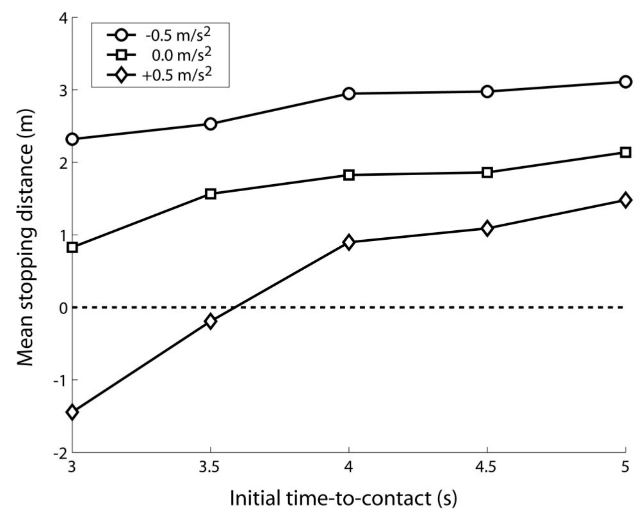

Figure 15. Mean final stopping distance (in meters) as a function of initial time to contact (in seconds) for the negative, zero, and positive external force conditions in Experiment 4. A negative stopping distance indicates that the observer stopped after colliding with the sign.

The results of Experiment 4 are also difficult to resolve with the tau-dot model because $\dot{\tau}$ specifies the sufficiency of current deceleration regardless of whether the actor's deceleration is due to braking, external forces, or a combination of both. To understand why the findings are inconsistent with the predictions of the tau-dot model, suppose that the ideal deceleration at some moment during approach is 6 m/s^2. Further, suppose that the actor's deceleration due to braking is 5 m/s^2 and that there is a strong headwind that contributes an additional 2 m/s^2 of deceleration. Because the actor's total deceleration due to braking and external forces (7 m/s^2) exceeds the ideal deceleration (6 m/s^2), $\dot{\tau}$ is greater than −0.5, indicating that the actor should decrease deceleration to avoid stopping too soon. In other words, because $\dot{\tau}$ tells the actor whether current total deceleration (i.e., due to braking and external forces) is sufficient, participants should not have been biased by the external force. Thus, the effects of external forces observed in Experiment 4 contradict the predictions of the tau-dot model as well as any other model based on the assumption that actors rely on information about the sufficiency of their current deceleration (e.g., Andersen et al.'s, 1999, constant deceleration model).

General Discussion

To avoid a collision with an obstacle in the path of motion by braking, it is both necessary and sufficient to keep the ideal

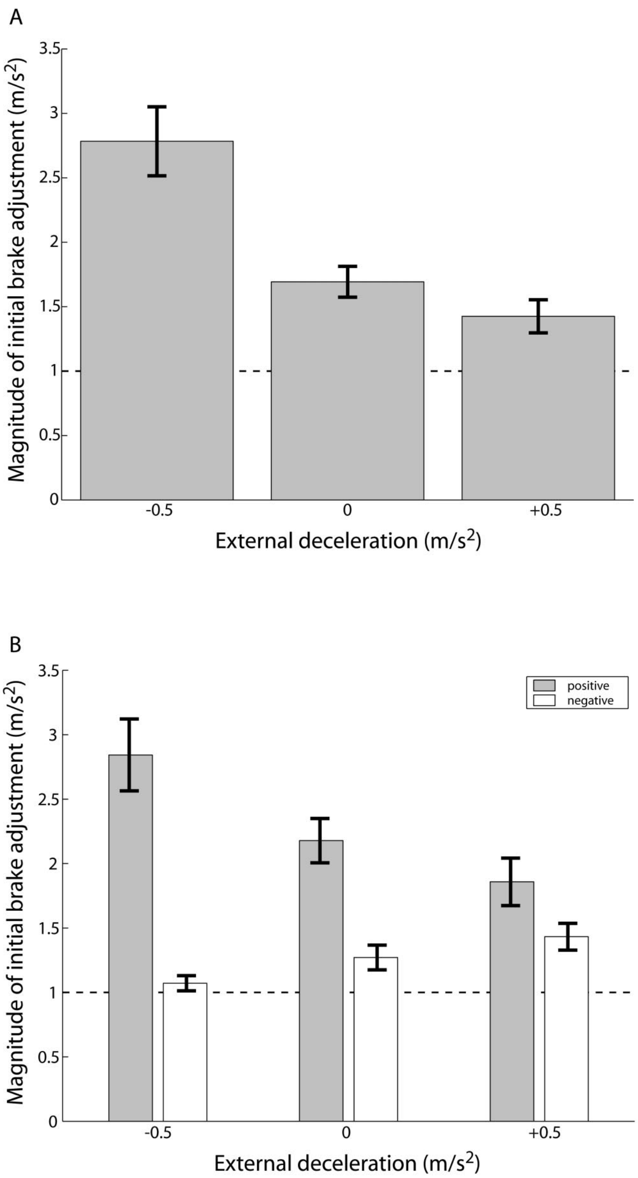

Figure 16. Mean magnitude of initial (A) and subsequent (B) brake adjustments for all three external force conditions in Experiment 4. In Figure 16B, solid bars correspond to positive brake adjustments, and open bars correspond to negative brake adjustments. Error bars indicate ±1 standard error. m/s^2 = meters per second squared.

deceleration below the maximum available deceleration of the brake. Ideal deceleration could be perceived on the basis of GOFR and τ, but maximum deceleration is a property for which there is no optical information. Furthermore, maximum deceleration depends on a variety of factors other than brake strength, some of which can change rapidly. The purpose of this study is to explore the mechanisms by which actors successfully control braking across a variety of conditions by adapting to changes in maximum deceleration.

In Experiment 1, brake strength was manipulated as a between-subjects variable with three levels of maximum deceleration. Participants in the weak brake condition initiated brake adjustments at smaller values of ideal deceleration than participants in the medium and strong brake conditions. When ideal deceleration was expressed as a percentage of maximum deceleration in each condition, however, all three groups initiated brake adjustments at the same value. To investigate the rate of calibration, I manipulated brake strength as a blocked variable in Experiment 2 and conducted the same analyses for each block. Participants completely calibrated to brake strength within 25 trials and recalibrated to a change in brake strength within 25 to 50 trials. I performed a more stringent test of rapid recalibration in Experiment 3 by manipulating brake strength as a randomly presented within-subject factor. Although the information for recalibration is contained in the optical consequences of a single brake adjustment, analyses of the onset and magnitude of brake adjustments revealed little evidence to suggest that actors can recalibrate on the basis of a single brake adjustment. However, post hoc analyses did confirm that participants partially recalibrated on a trial by trial basis. When brake strength on the previous trial was weak (or strong), participants initiated brake adjustments earlier (or later) on the following trial. In Experiment 4, a positive or negative external force was added to the simulated motion of the actor on each trial. For positive brake adjustments, the tendency to overshoot was greater in the negative external force condition and less in the positive external force condition. The opposite pattern of results was observed for negative brake adjustments.

Can any of these results be explained by existing models of visually guided braking, such as Lee's (1976) tau-dot model? Perhaps actors adapt to changes in maximum deceleration by tuning the range of $\dot{\tau}$ values that are safe to tolerate before a brake adjustment is necessary. Although $\dot{\tau}$ is independent of maximum deceleration, the lowest value of $\dot{\tau}$ from which an actor could recover by slamming on the brakes does depend on maximum deceleration. That is, the stronger the brake is, the lower is the value of $\dot{\tau}$ that can be safely tolerated. One problem with this account is that the range of safe $\dot{\tau}$ values depends as much on current kinematic conditions as it does on maximum deceleration (Kaiser & Phatak, 1993). Specifically, the lowest value of $\dot{\tau}$ from which an actor could recover by slamming on the brakes (i.e., $\dot{\tau}_{\min}$) is equal to $(d_{current}/2D_{\max})-1$. In other words, $\dot{\tau}_{\min}$ would have to be recalibrated every time the actor makes a brake adjustment. When current deceleration is 50% of maximum deceleration, the lowest value of $\dot{\tau}$ that could be safely tolerated is -0.75. If the actor adjusts the brake to reduce deceleration to 25% of the maximum, then the lowest safe value of $\dot{\tau}$ would be -0.875. It seems unlikely that such recalibration could take place on a continual basis. Another problem is that the relation among current deceleration, maximum deceleration, and $\dot{\tau}_{\min}$ does not hold when current deceleration equals zero. Therefore, $\dot{\tau}_{\min}$ cannot be calibrated until braking is initiated, which makes it difficult to explain how actors time the initiation of braking.

In contrast, the results of the present study can be easily understood from the perspective that actors rely on information about ideal deceleration relative to maximum deceleration and make adjustments to keep the perceived ideal deceleration within the safe region (Fajen, 2005a). Within this framework, actors adapt to changes in brake strength by learning to adjust the metric in which information about ideal deceleration is detected. When the metric is adjusted so that it is always possible to stop when ideal deceleration measures less than 1.0 and never possible to stop when ideal deceleration measures more than 1.0, information about ideal deceleration is detected in units of maximum deceleration. This explains why participants in different brake strength conditions of Experiment 1 initiated brake adjustments at the same mean value of ideal deceleration expressed as a percentage of maximum deceleration. In addition, the results of Experiment 4 suggest that actors learn to adjust the position of the brake by mapping perceived ideal deceleration (relative to maximum deceleration) onto brake displacement (relative to maximum displacement). The presence of positive or negative external forces that contribute to the simulated motion of the actor shifts this mapping, accounting for the pattern of systematic biases observed in the magnitude of individual brake adjustments. Taken together, the results provide additional support for the hypothesis that actors control braking by perceiving ideal deceleration in units of maximum deceleration and making adjustments to keep ideal deceleration within the safe region.

Calibration, Internal Models, and Visually Guided Action

The rationale for this study was that traditional error-nulling models of visually guided action fall short on the grounds that they fail to acknowledge the significance of maximum action capabilities. Similar criticisms have been levied against these models by other investigators. Loomis and Beall (1998, 2004) have pointed out that the guidance of action on the basis of information in optic flow is not enough to understand how movements are controlled. They argued that a complete understanding of visually guided action must also include a role for internal models of the spatial envelop and plant dynamics of the actor's body or vehicle. Indeed, the calibration observed in the present study could easily be interpreted as evidence of the formation of an internal model in which knowledge of maximum deceleration is represented. One could compare such knowledge with the estimate of ideal deceleration at each moment to determine whether a brake adjustment is necessary to keep ideal deceleration within the safe region.

Although the data alone do not allow us to rule out such an interpretation, the same concerns that were raised in the introduction force us to rethink what is meant by "forming an internal model." For Loomis and Beall (1998), internal models of plant dynamics are "memory-based representations [that] are not specific to the current environmental circumstances . . . but are instead general and thus deployable across a variety of circumstances" (p. 275). The question is, In what units is the knowledge contained in an internal model (e.g., about maximum deceleration) represented? For the same reason that ideal deceleration cannot be perceived in extrinsic units (i.e., such units are arbitrary and meaningless to actors), knowledge of maximum deceleration cannot be represented in extrinsic units. More important, knowledge of maximum deceleration represented in memory independently of perception would only be necessary if the metric in which ideal deceleration is perceived is fixed. If perceptual systems are capable of flexibly adjusting the scale in which information is detected, then the need for a memory-based representation of maximum deceleration that exists independently of perception would be eliminated. From this perspective, the only sense in which knowledge of brake strength is represented is in terms of the size of the units to which the perceptual system is calibrated. An interesting question for future research is the extent to which such scaling transfers from one task to another.

The claim that an action-independent representation of three-dimensional space is necessary for the control of action is also open to question. First, the fact that ideal deceleration can be calculated from spatial variables (e.g., $v^2/2z$) does not mean that actors need to estimate distance and speed to perceive ideal deceleration. They can perceive ideal deceleration directly by detecting information in optic flow (e.g., GOFR/2τ). Second, if information about ideal deceleration is detected in units of maximum deceleration, then perceived ideal deceleration is better understood as *action dependent* because changes in maximum deceleration will result in changes in the detection of information. In this sense, one's action capabilities can influence one's perception of the world. Proffitt and colleagues (Proffitt, Bhalla, Grossweiler, & Midgett, 1995; Proffitt, Stefanucci, Banton, & Epstein, 2003) have come to the same conclusion on the basis of a set of findings demonstrating that judgments of distance and surface slope were affected by the amount of effort required to walk to the object or climb the slope. For example, verbal judgments of surface slope increased when participants put on a heavy backpack or were in a state of fatigue or poor physical fitness. The authors concluded that the actor's behavioral potential influenced his or her perception of the environmental layout. From the perspective adopted in this article, the influence of action on perception reflects the fact that information is detected in intrinsic units relevant to one's action capabilities. In sum, the hypothesis that information is detected in intrinsic units corresponding to one's action capabilities has important theoretical implications that reflect the fact that perception and action are deeply intertwined. For an actor engaged in a visually guided action, such as braking, one could argue that there is no meaningful sense in which perceived three-dimensional space is represented independently of action and no meaningful sense in which the plant and controller dynamics are represented independently of the detection of information.

One important methodological implication is that researchers need to exercise caution when interpreting data from experiments that require participants to make passive judgments about tasks that normally require active control. For example, Andersen et al. (1999) asked participants to watch displays simulating constant deceleration approaches to a stop sign. The displays terminated before the stop sign was reached, and participants judged whether they would have collided or stopped short. This is equivalent to asking participants to judge whether current deceleration is sufficient to avoid collision, which, from the present perspective, is not relevant to the control of braking. An alternative task more consistent with the current perspective is to ask participants to judge whether it was still possible to stop when the displays were terminated. To perceive this property, however, participants must calibrate information about ideal deceleration to maximum deceleration. Information for calibration is normally available in the optical consequences of individual brake adjustments, but is eliminated in a passive judgment task. Thus, the more serious problem with this task is that the normally available feedback that is necessary to scale information into action relevant units is unavailable.

Affordances and Body Scaling Versus Action Scaling

The proposed scaling of information in units relevant to one's action capabilities is intended to be analogous to the "body scaling" of spatial information discussed in the literature on affordances. Affordances provide descriptions of the environment in terms of what actions are possible and what actions are not possible (Gibson, 1986; Turvey, 1992). Classic examples of affordances include "climbability" and "sit-on-ability," both of which are defined by leg length (Mark, 1987; Warren, 1984), and "passability," which is defined by shoulder width (Warren & Whang, 1987). Such affordances are said to be body scaled because properties of the surface layout must be scaled to the relevant dimension of the actor's body. Analogously, there are other possibilities for action that are defined not by the actor's body dimensions but by his or her action capabilities. For example, the "catchableness" of a fly ball and the "crossability" of a road depend on the actor's maximum running speed (Oudejans, Michaels, Bakker, & Dolne, 1996; Oudejans, Michaels, van Dort, & Frissen, 1996). The affordance for visually guided braking—that is, whether it is still possible to stop—is also action scaled because it is defined by maximum deceleration, which is an action capability and is not necessarily dependent on the actor's body dimensions. Despite the differences between body scaling and action scaling, the principle is the same—the world is perceived in an intrinsic metric that is relevant to performing the action. Thus, the finding from Experiment 1 that actors in the weak, medium, and strong brake strength conditions initiated brake adjustments at the same mean value of ideal deceleration expressed in units of maximum deceleration is analogous to the findings of Warren (1984), who demonstrated that judgments of stair climbability were the same for short and tall actors when stair height was scaled to leg length.

One aspect of action scaling that differs from the classic examples of body scaling is that the relevant scalar is not available in the optic array. Body dimensions, such as leg length and shoulder width, that define many affordances (e.g., climbability, sit-on-ability, passability) are roughly proportional to eye height (Mark, 1987; Warren & Whang, 1987). Because surface heights are already scaled to the actor's eye height in the optic array (Lee, 1974; Sedgwick, 1973), some body-scaled affordances can be perceived directly without knowledge of body dimensions. In the case of action-scaled affordances, such as the affordance for braking, the relevant scalar (e.g., maximum deceleration) is not available in the optic array. Thus, action scaling must involve a different process. Earlier, it was suggested that one could find the right scalar by using the optical consequences of one's actions to adjust the metric in which information is detected until 1.0 reliably separates possible from impossible actions. This means that action scaling requires at least minimal experience to maintain calibration and to compensate for changes in action capabilities. It also means that actors do not rediscover their capabilities and the limits of the actions anew each time they perform the action (Mark, 1987; Oudejans, Michaels, Bakker, & Dolne, 1996). If actors are truly able to rediscover their action capabilities each time they perform an action, they should be able to rapidly recalibrate to sudden changes in their action capabilities. The results of Experiment 3, in which actors failed to completely recalibrate when maximum deceleration was manipulated on a trial-by-trial basis, provide no support for the claim that action capabilities are continually rediscovered

Implications for Other Visually Guided Actions

The focus of this study is on visually guided braking, but the same principles apply to other visually guided actions (Fajen, 2005b). Like the existing models of braking, models of steering (Wann & Land, 2000; Wann & Swapp, 2000), fly ball catching (Chapman, 1968; McBeath, Shaffer, & Kaiser, 1995; Oudejans, Michaels, Bakker, & Davids, 1999), interception by hand (Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994), and interception on foot (Fajen & Warren, 2004; Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999) are based on the assumption that actors rely on information about the sufficiency of their current state and make adjustments to null the difference between their current state and the state required to perform the action. However, the actor's maximum action capabilities impose analogous constraints on the successful performance of these actions. Given the task of fly ball catching, for example, the outfielder must keep the running speed required to reach the landing location in time to catch the ball between zero and the maximum running speed. Just as a driver must scale information about ideal deceleration to maximum deceleration, an outfielder must scale information about required running speed to maximum running speed. Thus, the calibration of perception and action is likely to play a necessary role in all visually guided actions.

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