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RESEARCH ARTICLE

Rapid recalibration based on optic flow in visually guided action

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Abstract Action capabilities are always subject to limits. Whether on foot or in a vehicle, people can only move so fast, slow down so quickly, and turn so sharply. The successful performance of almost any perceptual-motor task requires actors to learn and continually relearn their ever-changing action capabilities. Such learning can be considered an example of perceptual-motor calibration. The present study includes two experiments designed to address basic questions about the nature of this calibration process. Subjects performed a simulated braking task, using a foot pedal to slow down to a stop in front of an obstacle in the path of motion. At one point in the experiment, the strength of the brake was increased or decreased unbeknownst to subjects, and behavior before and after the change in brake strength was analyzed for evidence of recalibration. Experiment 1 showed that actors rapidly recalibrate following a change in brake dynamics, even when they are unaware of the change. In Experiment 2, the scene turned black one second after braking was initiated. Subjects still recalibrated following the change in brake strength, suggesting that information in the sensory consequences of the initial brake adjustment is sufficient for recalibration, even in the absence of feedback about the outcome (i.e., in terms of final position error) of the task. Discussion focuses on the critical but often overlooked role of calibration in continuously controlled visually guided action, and the nature of the information used for recalibration.

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Introduction

Anyone who has ever rented an automobile has experienced the uneasy feeling of not "knowing" the car's steering wheel, accelerator, or brakes. Each car responds in a different way to a turn of the steering wheel, or a change in the pressure applied the accelerator or brake pedal. The first time the driver depresses the brake pedal in response to a rapidly decelerating lead vehicle, or hits the accelerator to overtake a slowly moving lead vehicle, he or she may find that the car responded differently than expected. Oftentimes, the driver may need to make jerky and inefficient corrective movements to avoid a collision. Eventually, with little or no conscious effort (but some amount of experience maneuvering the automobile), the driver will come to know how the car responds.

Unfamiliarity with the vehicle's dynamics can affect not only the driver's control of the vehicle, but also his or her decision making. Suppose an animal suddenly darts out in front of an automobile. If the automobile is moving slowly and the animal is far enough away, it may be possible to avoid a collision by slowing down. But if the car is moving too quickly or the animal is too close, then the driver must swerve out of the way (Tresilian et al. 2004). The driver may have no more than a split second to choose between one of two possible actions—avoiding a collision by slowing down or avoiding a collision by swerving. The critical boundary that separates these two possible actions is primarily determined by two factors: (1) the rate of deceleration that is required to avoid a collision (which is a function of approach speed and distance), and (2) the maximum possible rate of deceleration of the automobile.[1] If the deceleration required to stop is less than the maximum deceleration, then it is possible to avoid a collision by slowing down. But if the required deceleration exceeds maximum deceleration, the driver must swerve to avoid a collision. Clearly, the correctness of the driver's decision to slow down or swerve depends on how well he or she knows the vehicle's brake dynamics. In a similar manner, other split-second driving decisions, such as whether to overtake a slowly moving lead vehicle (Gray and Regan 2000, 2005), initiate a left-turn at an intersection (Gray 2004), or decelerate before entering a sharp bend in the road, depend on knowledge of the vehicle dynamics.

Such phenomena are not at all restricted to automobile driving. Knowing the dynamics of a system that must be controlled, whether it be a vehicle or one's own body, is essential for almost every perceptually guided action (Fajen 2005b). Just as drivers must know the dynamics of their automobiles, athletes must know the dynamics of their bodies. When a fly ball is hit weakly into short centerfield, the centerfielder must take his or her running capabilities into account when deciding whether to attempt to catch the ball on a fly or let it hit the ground and catch it on a bounce (Oudejans et al. 1996b). Even routine tasks, such as deciding whether or not to cross the street in front of an approaching vehicle, depends critically on knowing the action capabilities of one's body (Oudejans et al. 1996a).

Although it is quite clear that actors must (in some sense and with a certain degree of precision) know the dynamics of the systems that they control, it is much less clear how they come to know such properties. Unlike other action-relevant properties, the dynamics of a system are "invisible" in the sense that there is no perceptual information (at least in the usual sense) about such properties as the maximum rate of deceleration of one's automobile or the maximum running speed of one's body. To complicate matters, the dynamics of vehicles and bodies are rarely fixed. An automobile's maximum deceleration can vary with load, traction, surface slope, and the condition of the brake pads, and an outfielder's running speed can depend on fatigue, injury, and fitness. Thus, actors must not only learn, but also continually relearn the ever-changing dynamics of the systems that they control.

Such relearning can be thought of as an example of perceptual-motor recalibration (Rieser et al. 1995; Bingham and Pagano 1998; Bhalla and Proffitt 1999; Durgin and Pelah 1999; Withagen and Michaels 2004; Bruggeman et al. 2005; Durgin et al. 2005; Withagen and Michaels 2005; Jacobs and Michaels 2006). Generally speaking, calibration establishes the relationship between the units in which measurements are taken and other known units (Bingham and Romack 1999). For example, measuring the distance between two points would be useless if the relation between the units in which the measurement was reported and some known unit of distance (e.g., meters, inches) was not established. Only when this relationship is established through calibration can one make use of the measurement. Similarly, perceptual-motor calibration is necessary to establish a relationship between the units in which the relevant information is detected and the units in which the action is executed (Fajen 2005b, 2005c). Information about how hard to brake is available in optic flow (Fajen 2005a).[2] To be useful, such information must be calibrated in such a way that it tells the driver how hard to brake in units that are related to the actor's braking capabilities (i.e., in intrinsic units). In the case of automobile driving, deceleration is controlled by displacing the brake pedal. So proper calibration establishes a direct mapping from information in optic flow about how hard to brake onto positions of the brake pedal. That is, information in optic flow tells a properly calibrated driver about the percentage of maximum brake displacement that is necessary to avoid a collision, or (if the required deceleration is more than 100% of maximum deceleration) that safe stopping is no longer possible within the limits of his or her braking capabilities.

The present study includes two experiments designed to address basic questions about the nature of this recalibration process. In both experiments, subjects performed a simulated braking task, using a foot pedal to slow down to a stop in front of the obstacle (a row of stop signs) in the path of motion. The strength of the brake was manipulated unbeknownst to subjects, and behavior before and after the change in brake strength was analyzed for evidence of recalibration. Experiment 1 was concerned with the rate at which actors recalibrate following a change in brake dynamics, and whether explicit awareness of the change is necessary for recalibration. The aim of Experiment 2 was

[1] Maximum deceleration, in turn, is a function of many factors, including the strength of the brake, the condition of the brake pads, surface traction, slope, etc.

[2] The constant rate of deceleration that would bring the actor to a stop exactly at the intended location, which I refer to as *ideal deceleration*, is equal to $v^2/(2 \times z)$, where v is approach speed and z is distance. v/z is equal to the inverse of the amount of time remaining until the driver reaches the intended location assuming constant velocity, which Lee (1976) called *time-to-contact*, and is specified by the ratio of the rate of optical expansion $\dot{\theta}$ to the optical angle θ (or $1/\tau$, where $\tau = \theta/\dot{\theta}$). As long as eye height is fixed, which it typically is for tasks that involve braking, speed is specified by *global optic flow rate (GOFR)*, which is the rate of optic flow of the ground texture underneath the actor (Larish and Flach 1990; Warren 1982). Substituting $\dot{\theta}/\theta$ for v/z and *GOFR* for v, ideal deceleration can be expressed in terms of optical variables as $GOFR \times \dot{\theta}/\theta$.

to determine whether the information for recalibration lies in feedback about the outcome of the task or in the optical consequences of individual movements.

Experiment 1

Experiment 1 was concerned with the rate at which actors recalibrate following a change in the strength of the brake, and whether actors must be consciously aware of the change to recalibrate. The brake pedal was programmed so that the simulated rate of deceleration (d) was proportional to pedal position (p); that is, $d = k \times p$, where k is the gain of the brake. Pedal position ranged from 0 to 1, so k corresponds to the maximum rate of deceleration that can be achieved by applying full brake pressure.

In a previous study (Fajen 2005c), brake gain was randomly manipulated on each trial. Subjects tended to initiate deceleration earlier and brake harder when brake strength was weak on the previous trial, and later and less hard when brake strength was strong on the previous trial. Such changes suggest that subjects were able to rapidly recalibrate. However, the changes were much smaller than one would expect if subjects completely recalibrated to the strength of the brake on the previous trial. Thus, it appears that actors can partially, but not completely recalibrate within a single approach.

Experiment 1 was designed to determine how long it takes to completely recalibrate. Three groups of participants completed ten blocks of fifteen trials. In Group A, brake gain (k) decreased from 12 m/s^2 in blocks #1 through #5 to 9 m/s^2 in blocks #6 through #10. In Group C, brake gain increased from 6 m/s^2 in blocks #1 through #5 to 9 m/s^2 in blocks #6 through #10. Group B was a control group whose brake gain was fixed at 9 m/s^2 for all ten blocks.

During the first five blocks, subjects in Group A, who were calibrated to the strong brake, should initiate deceleration later and subjects in Group C, who were calibrated to the weak brake, should initiate deceleration earlier compared to the control group (B). Immediately following the change in brake strength on block #6, subjects in Groups A and C should exhibit biases—those in Group A should undershoot and be more likely to crash, and those in Group C should overshoot and be more likely to stop short of the target. The rate at which these biases disappear with practice provides a measure of the rate of recalibration. When subjects are completely recalibrated, the behavior of all three groups should be indistinguishable.

Because trials last several seconds, and because visual information is continuously available, subjects may have enough time to correct for undershoots or overshoots even without recalibrating. If so, then the effects of the brake strength manipulation, especially on final stopping distance, may be weak. To provide an additional test of recalibration, each block of 15 trials included five “blackout” trials randomly interleaved with ten normal trials. On blackout trials, the scene disappeared and was replaced by a black screen at the moment that braking was initiated. Participants were instructed to do their best on blackout trials to adjust the brake so that they would come to a stop when they thought that they reached the stop signs. The distance to the stop sign at the end of blackout trials provides a sensitive measure of recalibration because subjects cannot use visual feedback on such trials. Thus, until subjects recalibrate following the change in brake strength between blocks #5 and #6, they should exhibit a bias to stop after colliding with the stop sign when brake strength is suddenly decreased (Group A), and before reaching the stop sign when brake strength is suddenly increased (Group C).

The second goal of Experiment 1 was to determine whether recalibration is a deliberate process that requires explicit awareness of a change in brake strength, or a more subtle process that can occur even when the actor is unaware of the change in brake strength. After the end of the experiment, participants were given a post-test questionnaire in which they were asked to report whether they noticed changes in several properties, one of which was the strength of the brake.

Method

Participants

Thirty-six students participated. Twelve were assigned to each group. All subjects had normal or corrected-to-normal vision, and a valid driver’s license or permit. Data from three of the 36 subjects were excluded because these subjects did not follow instructions.

Displays and apparatus

The simulated environment was developed in-house using C++ and OpenGL and generated by a Dell Precision 530 Workstation. The display was rear-projected by a Barco Cine 8 CRT projector onto a 1.8 m × 1.2 m screen at a frame rate of 60 Hz and a resolution of 1,280 × 1,024. The displays simulated observer movement along a linear path toward a row of three red and white octagonal stop signs (see Fig. 1a). The center of each stop sign was at the same height as the simulated eye height (1.1 m). The sky was light blue, and the ground was gray cement-textured. Figure 1B shows the image that was used to tile the ground plane. Each tile was stretched across a 30 m × 30 m area, which allowed for good contrast at low spatial frequencies

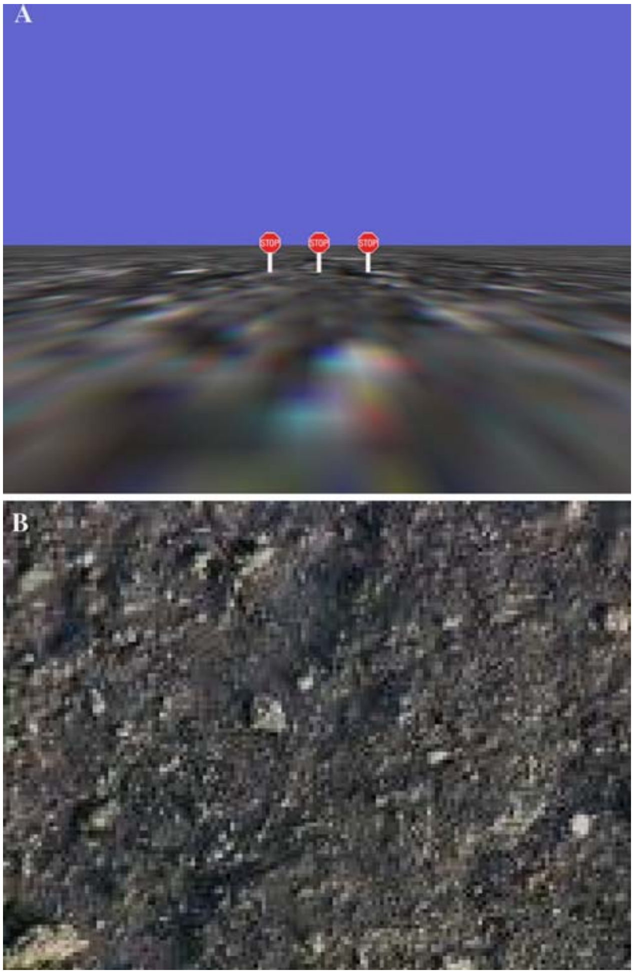

Fig.1 Sample screen shot of displays used in Experiment 1 (**a**). Ground textured used in both experiments (**b**)

(<0.5 cycles/m) and gradually less contrast at higher spatial frequencies. When the textured ground plane was projected onto the projection screen and self-motion was simulated, the displays provided salient optic flow in both the foreground and background.

Subjects sat in a chair whose height and position was adjusted so that the subject's head was near the projectively correct viewing position 1.1 m above the floor and 1 m from the screen. Braking was controlled using an ECCI Trackstar 6000 foot pedal system (Minneapolis, MN). Participants increased deceleration by pushing on the left-most of two foot pedals. Pedal position was sampled every frame and used to update the simulated rate of deceleration on the subsequent frame so that deceleration was proportional to pedal position. Deceleration ranged from 0 m/s^2 in the neutral position to maximum deceleration in the down most position. The foot pedal was spring loaded to provide resistance in proportion to displacement from the neutral position.

Design

There were ten blocks of trials and fifteen trials per block. Within each block, there were five initial speeds (9, 10, 11, 12, and 13 m/s) and initial distance varied randomly between 50 and 60 m. In Blocks #1 through #5, the maximum rate of deceleration was 12 m/s^2 for Group A, 9 m/s^2 for Group B, and 6 m/s^2 for Group C. In Blocks #6 through #10, the maximum rate of deceleration was 9 m/s^2 for all three groups. Prior to the experiment, participants completed several brief practice blocks designed to familiarize themselves with the task.

Procedure

Participants initiated each trial by pressing the trigger button on a joystick. The scene appeared and simulated motion toward the stop signs began immediately. Participants were encouraged to make smooth, natural brake adjustments as if they were driving a real car, and to avoid waiting until the last possible moment and slamming on the brakes. To discourage participants from adopting such a strategy, a skidding sound was played whenever the participant applied the maximum rate of deceleration. The trial ended when the participant came to a stop. Immediately following the last trial, participants were asked to complete the post-test questionnaire. The entire experiment lasted less than 1 h.

Post-test questionnaire

The post-test questionnaire consisted of a list of five items (initial speed, initial distance to the stop signs, size of the stop signs, strength of the brake, and height above the ground) and three response categories (definitely changed, may have changed/not sure, definitely did not change). Participants were instructed to indicate whether or not they noticed that any of the items on the list changed at any point during the experiment by placing a check mark in one of the three response categories.

Data analyses

The onset of braking was determined by looking for the first window lasting 200 ms (12 frames) over which deceleration changed by at least 5% of maximum deceleration. A useful measure of the timing of brake initiation is *ideal deceleration at brake onset*. Ideal deceleration is the constant rate of deceleration required to stop exactly at the intended location, and can be calculated using the following equation: $v_{onset}^2/(2 \times z_{onset})$, where v_{onset} is speed and z_{onset} is distance at the onset of braking (see Footnote

2). When an actor approaches a target at a constant speed (i.e., before braking is initiated), ideal deceleration increases gradually at first, and then more rapidly as the distance to the target decreases. Thus, if braking is initiated early in a given trial, then ideal deceleration at onset will be low because the actor can stop at the target by applying less deceleration than if braking is initiated later. In this sense, ideal deceleration at onset provides an indication of when braking was initiated.

The end of the initial brake adjustment was found by searching for the first window lasting at least 200 ms after brake onset during which deceleration was either held constant (±1% of maximum deceleration) or decreased. Figure 2 shows data from two sample trials with the initial brake adjustment indicated by the gray region. The magnitude of each initial brake adjustment was calculated by first taking the change in deceleration from the beginning to the end of the adjustment. For the two sample trials shown in Fig. 2a, b, the change in deceleration was 2.18 and 5.71 m/s^2, respectively. The change in deceleration that would be required to reach the ideal deceleration was then calculated. For undershoots, the required change in deceleration was calculated by taking the difference between the actual deceleration at the beginning of the adjustment and the ideal deceleration at the end of the adjustment. For overshoots, the difference between the actual deceleration at the beginning of the adjustment and the ideal deceleration at the overshoot frame (see Fig. 2b), rather than the end of the adjustment, was used. This is because ideal deceleration reverses direction at the overshoot frame. For the two sample trials in Fig. 2, the required change in deceleration was 2.73 and 4.57 m/s^2, respectively. The change in deceleration was then divided by the required change in deceleration

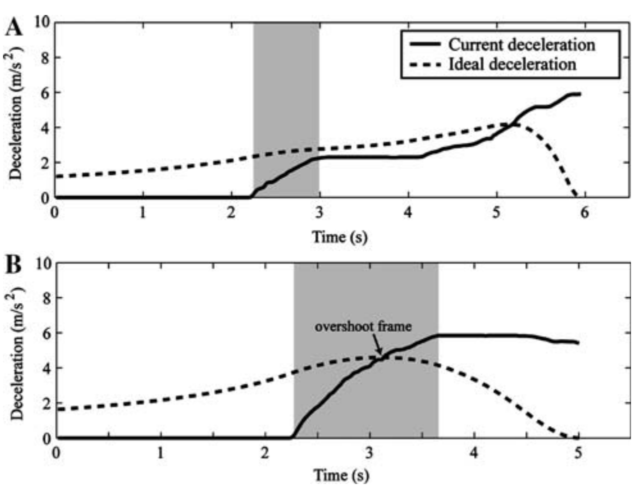

Fig. 2 Sample trials used to illustrate analysis of brake onset and brake adjustment magnitude

such that values less than 1.0 indicate undershoots (requiring a subsequent increase in deceleration to avoid a collision), and values greater than 1.0 indicate overshoots (requiring a subsequent decrease in deceleration to avoid stopping before reaching the stop sign). A value of 1.0 indicates that the actor adjusted deceleration by exactly the amount that is needed to stop at the stop sign without making any further adjustments along the way. For the sample trials in Fig. 2, the scaled magnitude equals 0.80, indicating an undershoot by 20%, and 1.25, indicating an overshoot by 25%.

Results and discussion

Analyses focused on the effects of brake strength on three dependent measures: (1) the timing on brake initiation on normal trials, (2) the magnitude of the initial brake adjustment on normal trials, and (3) final stopping distance on blackout trials.

Ideal deceleration at onset (normal trials)

To measure the timing of brake initiation, mean ideal deceleration at brake onset was calculated for each block. Recall that ideal deceleration is the rate of deceleration that would bring the actor to a stop exactly at the intended location without making any further adjustments, and that ideal deceleration increases until braking is initiated (see the "Data analyses" section of the Methods for more details). Thus, lower values of ideal deceleration at onset indicate that braking was initiated earlier, and vice-versa. Not surprisingly, subjects who are calibrated to a weak brake tend to initiate braking at lower values of ideal deceleration (i.e., earlier) than subjects calibrated to a strong brake (Fajen 2005c). This was apparent in the first five blocks of Experiment 1, in which subjects in Groups A and C initiated deceleration later and earlier, respectively, compared to subjects in the control group (Group B; see Fig. 3a). Following the change in brake strength beginning on block #6, subjects in Group A began to initiate braking earlier and subjects in Group C began to initiate braking later. A significant group × block interaction, F (18,270) = 8.49, $P < 0.01$, was followed up by an analysis of the simple main effect of group for each block. The effect of group was significant ($\alpha < 0.05$) for blocks #1 through #6, but not beyond. Contrast effects showed that Groups A and C differed significantly from the control group (B) in blocks #1 through #5. In block #6, only Group A differed from the control group. Thus, almost immediately following the change in brake strength, participants began to recalibrate to the change in brake strength by adjusting brake initi-

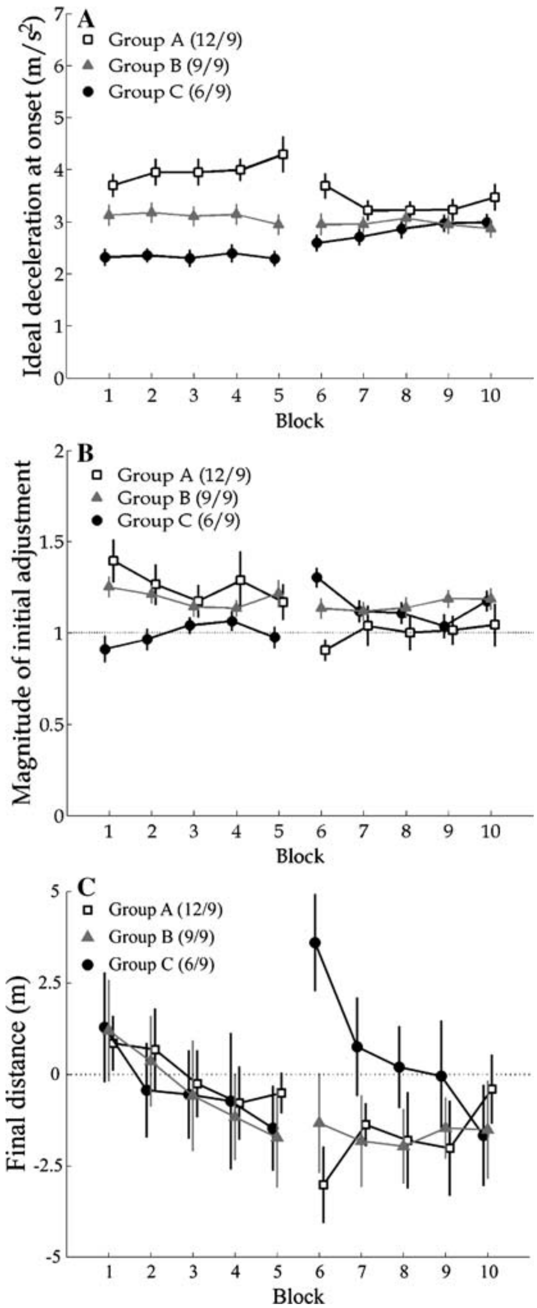

Fig. 3 Ideal deceleration at brake onset (**a**), magnitude of initial brake adjustment (**b**), and final stopping distance (**c**) as a function of block for all three groups in Experiment 1. In **b**, the magnitude of initial brake adjustment is scaled so that values less than 1.0 correspond to undershoots and values greater than 1.0 correspond to overshoots. In **c**, a positive final stopping distance indicates that the subject stopped before reaching the stop signs, and a negative stopping distance indicates that the subject stopped after passing through the stop signs

ation time. The results of the analysis of ideal deceleration at onset in blackout trials (not shown) were nearly identical, which is not at all surprising as the screen did not go black until after the onset of braking.

Magnitude of initial adjustment (normal trials)

Mean initial brake adjustment magnitude is plotted as a function of block for all three groups in Fig. 3b. Brake adjustment magnitude was scaled in such a way that values less than 1.0 correspond to undershoots (requiring a subsequent increase in deceleration to avoid colliding) and values greater than 1.0 correspond to overshoots (requiring a subsequent decrease in deceleration to avoid stopping too far away). Again, the group × block interaction was significant, F (18,270) = 6.68, $P < 0.01$. During the first five blocks, subjects in Groups A and B tended to overshoot. This is a common finding that mostly likely reflects a safety bias (Fajen 2005a, c). Brake adjustment magnitude for Group C was close to 1.0 and consistently less than brake adjustment magnitude for Groups A and B. The difference is mostly likely due to the fact that the brake in Group C was so weak for the initial conditions that it was much more difficult to overshoot. At the fastest initial speed and shortest initial distance, subjects would have to apply almost full brake pressure shortly after the onset of the trial to overshoot as much as subjects in Groups A and B.

Immediately following the change in brake strength (block #6), subjects in Groups A and C tended to undershoot and overshoot, respectively, compared to the control group. These differences were significant at the $\alpha < 0.05$ level. However, these biases quickly disappeared, as Groups A and C were indistinguishable from the control group beyond block #6. These findings are consistent with the evidence of rapid recalibration reported above.

Final stopping distance (normal and blackout trials)

On normal trials, subjects in all three groups consistently stopped within 2.5 m of the stop signs. On block #6, subjects in Group A stopped 0.98 m (SE = 0.17) closer to the stop sign and those in Group C stopped 0.95 m (SE = 0.35) farther away from the stop sign, compared to block #5. Although the change in brake strength affected mean final stopping distance, the effect was small. This is not at all surprising considering the fact that trials lasted several seconds and subjects had ample time to make use of the continuously available visual information to correct for initial overshoots and undershoots. In other words, even when subjects are calibrated to a brake that is stronger or weaker than the actual brake, errors in final stopping distance resulting from errors in calibration may be small. On blackout trials, however, visual information was cut off at the moment that braking was initiated, preventing subjects from correcting for overshoots and undershoots. In this sense, mean final stopping distance on blackout trials provides a more sensitive measure of changes in calibration that, unlike final stopping distance on normal trials, is uncontaminated by the use of continuously available information.

Figure 3c shows final stopping distance by block for each group on blackout trials, in which the scene turned black immediately after braking was initiated. A positive final stopping distance indicates that the subject stopped before reaching the stop signs, and a negative final stopping distance indicates that the subject stopped after reaching the stop signs. The large standard error bars indicate that there was a great deal of between-subject variability on blackout trials—some subjects tended to stop well before reaching the target whereas others stopped well after colliding with the target. This reflects the difficulty of performing a simulated braking task in the absence of visual information. In addition, there was a consistent trend throughout the first five blocks to stop later and later. Although these two results complicate the interpretation, evidence of rapid recalibration consistent with that reported using other measures was found. Subjects in Groups A and C stopped significantly later and earlier, respectively, on block #6 compared to the control group. Beyond block #6, the difference did not reach significance. Thus, although the variability complicates the interpretation, the results on blackout trials are consistent with the results on normal trials.

Post-test questionnaire

The pattern of responses to the post-test questionnaire item concerning detection of brake strength change suggests that recalibration can occur even when subjects are unaware of the change in brake strength (see Fig. 4). First, the change in brake strength was not reliably detected by subjects in Groups A and C. Although 41.67% of subjects in Group C reported that brake strength definitely changed, only 8.33% of subjects in Group A selected this response. Furthermore,

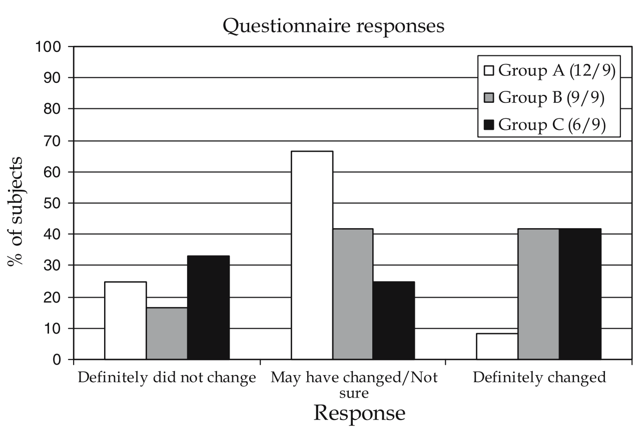

Fig. 4 Percentage of subjects for each response type for all three groups in Experiment 1

41.67% of subjects in Group B reported a definite change in brake strength despite the fact that brake strength was fixed throughout the entire experiment. This suggests that the responses of all subjects may have been based on a change in some trial parameter other than brake strength. Second, only 8.33% of subjects in Group A reported that brake strength definitely changed, despite the clear evidence of rapid recalibration by subjects in this group. Third, analyses of the individual subject data revealed that the three subjects in Group A and the four subjects in Group B who reported that brake strength definitely did not change exhibited the same pattern of recalibration that the other subjects exhibited. These results provide strong evidence that explicit awareness of a change in brake strength is not necessary for recalibration to occur.

Such findings complement those that suggest that explicit knowledge of a change is, by itself, not necessarily sufficient to elicit perceptual-motor adaptation to that change. For example, Nowak and Hermsdorfer (2003) measured the grip force that subjects applied with their thumb and forefinger when lifting a cup of water. After subjects place the cup back on the table, they used a straw to drink half of the water in the cup. Despite the fact that subjects knew the cup contained less water, and therefore required less grip force to pick up, they applied the same amount of grip force to pick up the cup a second time. It was not until subjects picked up the cup several more times that grip force was appropriately reduced. Thus, awareness of a change in the dynamics of the environment, and perceptual-motor adaptation to that change, can operate more or less independently. The findings of the present study help to reinforce this conclusion.

To summarize, the two major findings of Experiment 1 were that subjects are capable of rapidly recalibrating to a change in brake strength within approximately ten trials, and that recalibration can take place even when actors are unaware of the change in brake strength. The results on blackout trials provide additional evidence for rapid recalibration.

Experiment 2

Experiment 1 demonstrated that subjects can rapidly recalibrate to a change in brake strength, but did not allow us to draw any conclusions about the nature of the information that actors use to recalibrate. What tells actors that it is necessary to adjust the timing and magnitude of brake adjustments? One possibility is that recalibration results from feedback about the outcome (i.e., final position error) of the action. Immediately following a sudden decrease in brake strength (as experienced by Group A in Experiment 1), the likelihood of colliding with the target increases.

Similarly, the likelihood of stopping too short increases immediately following a sudden increase in brake strength (Group C in Experiment 1). It seems reasonable to assume that a sudden change in the likelihood of collisions or short stops would lead subjects to change the timing and magnitude of brake adjustments, even if they were unaware that the change resulted from a change in brake strength. This is analogous to the way in which feedback about the accuracy of hand movements has reportedly been used to recalibrate reaching (Bingham and Pagano 1998; Bingham et al. 2001) and catching (Jacobs and Michaels 2006), as well as the way in which feedback about the accuracy of perceptual judgments has been used to recalibrate perceived length by dynamic touch (Wagman et al. 2001; Withagen and Michaels 2004, 2005).

Feedback about trial outcome may not be the only, or even the primary means by which actors recalibrate. As soon as braking is initiated, the resulting change in deceleration affects the pattern of optic flow, as well as the inertial forces that act on the observer. Because such sensory consequences (i.e., reafference) depend on the strength of the brake, they may provide information for recalibration. Thus, the second hypothesis is that actors recalibrate on the basis of information in the sensory consequences of their actions well before feedback about the outcome of the trial is available. This is analogous to the way in which locomotion can be recalibrated by discrepant visual information (Pelah and Barlow 1996; Lackner and DiZio 1997).

These two hypotheses were tested in Experiment 2 by removing feedback about final position error, but leaving intact information for recalibration contained in optic flow. Two groups of subjects completed 15 blocks, each of which consisted of 10 trials. In Group A, brake strength decreased from 9 to 7 m/s^2 between the fifth and sixth blocks. In Group B (the control group) brake strength was fixed at 9 m/s^2 for all 15 blocks.[3] As in Experiment 1, the scene simulated linear self-motion toward a row of stop signs. Subjects were instructed to use the foot pedal to decelerate to a stop within a small, red target region located on the ground plane directly in front of the row of stop signs. Exactly one second after braking was initiated by the subject, the entire scene disappeared and the screen turned black. Subjects were instructed to continue braking even after the screen turned black and try to come to a stop within the red target region. The trial ended when speed reached zero.

To keep subjects focused on the task of stopping within the target region even after the scene disappeared, an audible tone was played if the subject successfully stopped within the target region. If the subject stopped either before or after the target region, then no tone was played. The tone motivated subjects to continue focusing on the task after the blackout, but provided no useful feedback for recalibration. This is because the tone's absence indicated only that the target was missed; it did not indicate whether the target was missed by stopping too soon or too late.

Although the tone provided no feedback for recalibration, subjects may still guess whether they stopped before or after the target, and recalibrate based on their guesses. However, this would require that subjects make accurate guesses about final position error. To measure the accuracy of such guesses, a screen appeared immediately after the end of each trial that resulted in a miss asking subjects to judge whether they stopped before reaching the target region or after passing through the target region. If subjects are able to recalibrate yet their judgments about trial outcome are inaccurate, then recalibration cannot be based on guessing about trial outcome.

Method

Participants

Twenty-four students participated. Twelve were assigned to each group. All subjects had normal or corrected-to-normal vision, and a valid driver's license or permit.

Displays and apparatus

The displays and apparatus were identical to those used in Experiment 1 with the following exceptions. First, a small, red target strip (3 m wide × 2 m long) was placed on the ground plane directly underneath the row of stop signs. Second, the range of initial speeds (13, 14, 15, 16, and 17 m/s) was faster and the brakes (9 and 7 m/s^2) weaker compared to those used in Experiment 1. This forced subjects to start braking earlier in the trial, which ensured that they would still be far away from the target region when the screen turned black. If they were too close to the target when the screen turned black, then it would have been too easy to stop within the target region. Third, immediately after the simulated speed reached zero, the trial ended and one of two things occurred. If the subject stopped within the target region, then an auditory tone was presented. Otherwise, a screen appeared asking subjects to indicate whether they thought they stopped before reaching the target region or crashed into the stop signs at the end of the target. The words "too short" and "crashed" appeared on the left and right sides of the screen, respectively. Subjects selected a response by pulling back on one of two

[3] Because there was nothing in Experiment 1 to suggest that recalibration to increases in brake strength is any different than recalibration to decreases in brake strength, we only tested two groups in Experiment 2 (i.e., a group whose brake strength decreased, and a control group).

paddles on the left or right sides of an input device. The selected response was highlighted, and subjects registered their response by pushing a button on the same input device.

Procedure

The procedure was similar to that used in Experiment 1. Prior to the experiment, subjects completed two practice sessions both lasting 30 trials. The screen did not turn black in the first practice session, so that subjects could familiarize themselves with the braking task. In the second practice session, the screen did turn black 1 s after brake onset to allow subjects to practice under the same conditions used in the actual experiment.

Results and discussion

Braking profiles

Before presenting the evidence for recalibration, it is important to inspect the braking profiles to rule out the possibility that subjects adopted an unnatural braking strategy to perform the task under the delayed blackout conditions used in Experiment 2. Braking profiles from Experiment 2 were compared with those on normal trials in Experiment 1. Figure 5a–b show representative profiles from one subject in Experiment 1 (normal trials only) and another subject in Experiment 2. (Note that braking profiles from different trials are temporally aligned based on the moment at which braking was initiated. Thus, the abscissa corresponds to the amount of time since braking was initiated, rather than the amount of time since the beginning of the trial as in Fig. 2). Under both normal conditions (Experiment 1) and delayed blackout conditions (Experiment 2), subjects generally increased deceleration for approximately one second. The mean duration of the initial adjustment on normal trials in Experiment 1 ($M = 0.95$ s, SE = 0.04 s) was nearly identical to that under the delayed blackout conditions of Experiment 2 ($M = 0.93$ s, SE = 0.05 s). Following the initial adjustment, subjects generally maintained deceleration for the duration of the trial or made small adjustments. Subsequent adjustments, which were identified by looking for trials in which deceleration changed by more than 5% of maximum deceleration after the end of the initial adjustment, were found on 74.7% (SE = 3.3%) of normal trials in Experiment 1 and 73.1% (SE = 3.6%) of trials in Experiment 2. In general, subjects in Experiment 1 made larger subsequent adjustments, which is not surprising because of the availability of visual information throughout the entire approach. Finally, once braking was initiated, subjects rarely released brake pressure completely (i.e., coasted). Coasting after brake initiation occurred on just 15.8% (SE = 2.3%) of normal trials in Experiment 1 and 3.5% (SE = 1.3%) of trials in Experiment 2. This rules out the possibility that subjects in Experiment 2 adopted an unnatural strategy, such as quickly decelerating to a manageable speed before blackout, completely releasing brake pressure after blackout, coasting until they thought they reached the target, and then slamming on the brakes. Rather, subjects in Experiment 2 behaved similarly to those in Experiment 1, with the exception that they made smaller brake adjustments after the end of the initial adjustment. Braking profiles were also similar to those shown in a recent study of real-world braking (see Fig. 1 in Rock et al. 2006). Thus, subjects in Experiment 2 did not adopt an unnatural braking strategy to perform the task under the delayed blackout conditions.

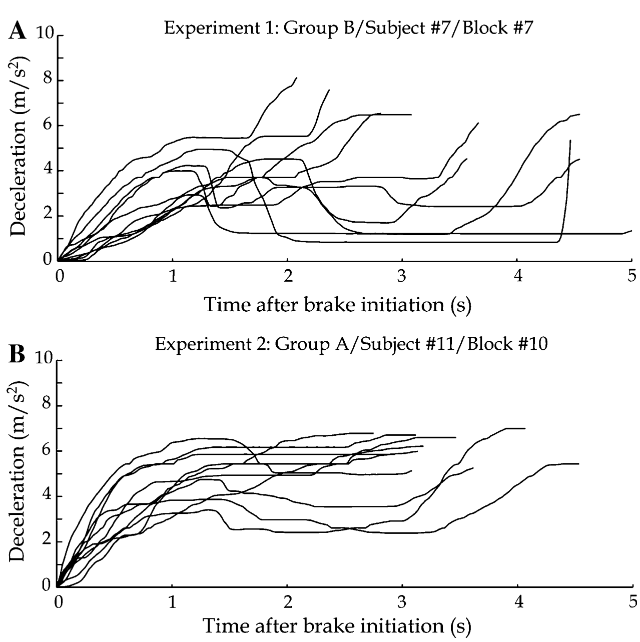

Fig. 5 Sample braking profiles from representative subjects in **a** Experiment 1and **b** Experiment 2

Ideal deceleration at onset

Following the change in brake strength on block #6, mean ideal deceleration at onset gradually decreased, suggesting that subjects in Group A learned to initiate braking earlier (Fig. 6a). However, the difference between groups did not reach significance in any block.

Initial brake adjustment magnitude

Immediately after the change in brake strength, subjects in Group A tended to make smaller initial brake adjustments,

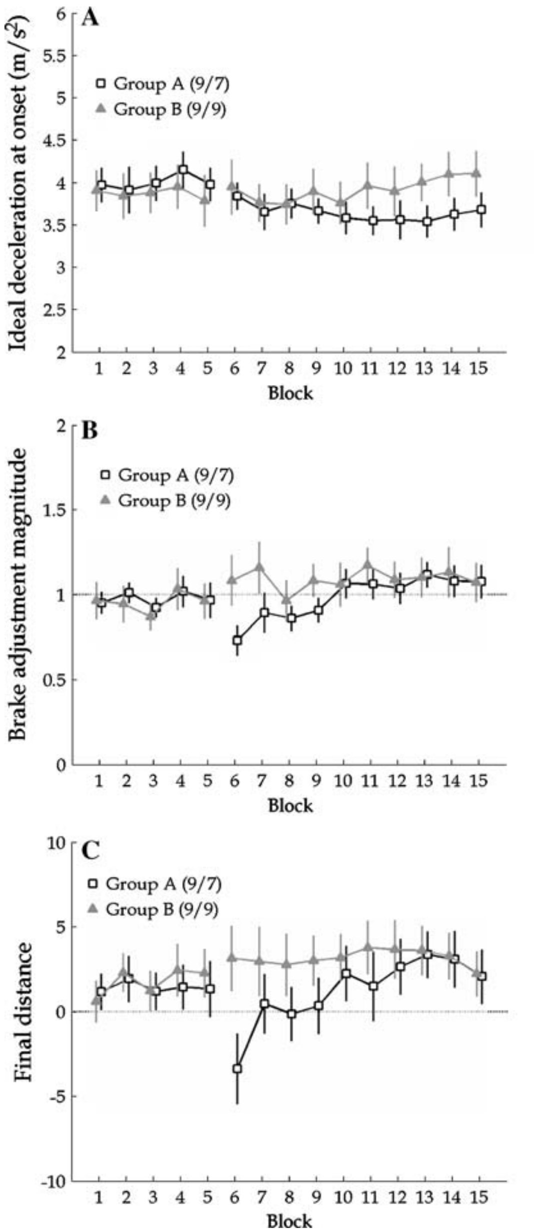

Fig. 6 Ideal deceleration at brake onset (**a**), magnitude of initial brake adjustment (**b**), and final stopping distance (**c**) as a function of block for both groups in Experiment 2

resulting in undershoots of ideal deceleration by approximately 27% (Fig. 6b). The tendency to undershoot indicates that subjects had not yet recalibrated to the change in brake strength. The difference between Groups A and B reached significance in block #6, but not thereafter.

Final stopping distance

The analysis of final stopping distance (Fig. 6c) was consistent with the results reported above. Immediately following the change in brake strength, subjects tended to travel further before stopping. The difference between Groups A and B was significant on block #6 only. Overall, the results were consistent across dependent measures—subjects exhibited evidence of recalibration within the first block of ten trials, and fully recalibrated within several blocks.

Taken together, these results provide evidence that actors can rapidly recalibrate to changes in brake strength on the basis of information in optic flow and without feedback about final position error. Immediately following the change in brake strength after block #5, participants tended to undershoot and stop after crashing into the target. With additional practice, they learned to brake earlier and harder, and were just as likely to stop short of the target as they were to stop behind it, suggesting that they rapidly recalibrated to the change in brake strength. Because the screen turned black one second after braking was initiated, recalibration could not have resulted from feedback about final position error.

Although it is possible to rule out the necessity of feedback about final position error, the fact that subjects heard an auditory tone whenever they stopped within the target region means that it is not possible to rule out an explanation based on a combination of information in optic flow and feedback about trial success or failure. However, it should be noted that subjects in Group A stopped within the target region on fewer than 20% of trials. On the remaining 80^{+}% of trials, subjects did not hear the auditory tone and therefore received no feedback about whether they stopped before or after the stop signs. Thus, subjects were able to rapidly recalibrate despite the fact that the feedback about trial success was infrequent. This suggests that feedback about trial success contributed little, if at all, to recalibration.

Results and responses

Although feedback about the outcome of the trial was removed, the possibility remains that subjects were able to guess whether they crashed or stopped short, and recalibrate on the basis on their guesses (rather than on the basis of optic flow). The pattern of responses to the post-trial question allows us to rule out this explanation. If recalibrate resulted from accurate guessing about final stopping position, then we would expect a close match between the response and the actual result. This was not the case. Figure 7a shows the percentages of each outcome (too short, on target, crash) as a function of block for subjects in Group A. Figure 7b shows the percentages of each response type. Despite the sharp increase in crashes immediately after the decrease in brake strength between blocks #5 and #6, post-trial responses were evenly distributed between “too short” and “crash.” Thus, subjects were

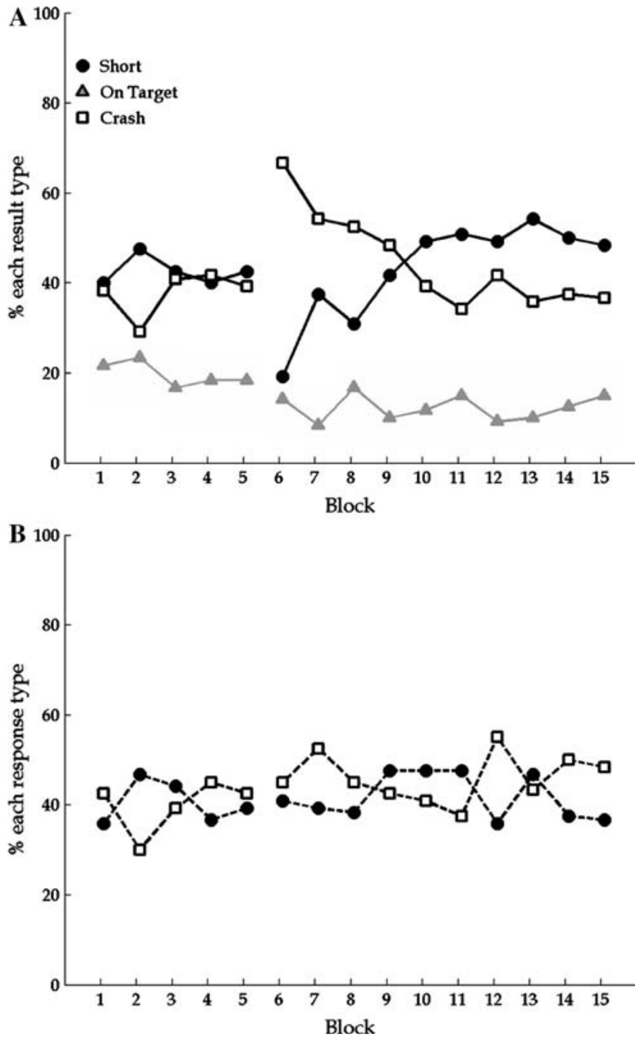

Fig. 7 Percentage of each result type (**a**) and percentage of each response type (**b**) as a function of block for Group A in Experiment 2

unable to accurately guess whether they stopped short or crashed. The possibility that recalibration was based on guesses about trial outcome, rather than optic flow, can be ruled out.

General discussion

The major findings of the present study are that: (1) actors performing a visually guided action are capable of rapidly recalibrating to changes that affect (the limits of) their action capabilities, (2) awareness of such changes is not necessary for recalibration, and (3) actors can recalibrate on the basis of information in the sensory consequences of their actions even in the absence of feedback about the outcome (in terms of final position error) of the task. The general discussion will focus on the theoretical implications of this study.

What are the implications for theories and models of visually guided action?

In the real world, actors' capabilities are constantly changing. Thus, the flexibility exhibited by subjects in the present study reflects that which is essential for successful performance across the range of conditions that are encountered in the real world. Considering the critical role that recalibration plays in the visual guidance of action, it is important to include mechanisms for recalibration in models of visually guided action. Presently, such mechanisms are almost always left out, reflecting the fact that the role of recalibration is often overlooked. Almost all models of continuously controlled visually guided action describe how actors use information in optic flow to null the error between the current and ideal state. Lee's (1976) tau-dot model of braking is an excellent example, but similar models exist for steering (Wann and Swapp 2000; Fajen 2001), interception on foot (Lenoir et al. 1999; Chardenon et al. 2004; Fajen and Warren 2004, 2007) and by hand (Peper et al. 1994; Montagne et al. 1999; Dessing et al. 2005), and fly ball catching (Chapman 1968; Michaels and Oudejans 1992; McBeath et al. 1995; McLeod et al. 2006). All of these models ignore the fact that that there are limits to actors' capabilities as well as the fact that these limits can change. Thus, they fail to explain how actors behave in ways that take the limits of their action capabilities into account, and adapt to changes that affect these action capabilities (see Fajen 2005b, c for further discussion).

What is the informational basis for recalibration?

The results of Experiment 2 demonstrated that actors can recalibrate on the basis of information in the optical consequences of the movements. In this section, I will explore the informational basis for recalibration in more detail, and consider two possible sources of recalibration information.

Anecdotal evidence, such as the rental car example given in the introduction, suggests that drivers have some (at least crude) expectation about the optical, vestibular, and/or somatosensory consequences that will result from applying so much pressure to the brake. The mismatch (if any) between the expected and actual sensory consequences could be used for recalibration. This would require some sort of feedforward or predictive modeling (Davidson and Wolpert 2005), similar to what has been proposed in studies of reaching and pointing (Wolpert et al. 1995) as well as manual tracking (Miall and Jackson 2006), to generate a prediction of the sensory consequences of the intended brake adjustment.

Another way in which information in optic flow could be used for recalibration was proposed by Fajen (2005b).

Recall from the Introduction, that ideal deceleration must always be perceived in intrinsic units that are defined by the strength of the brake to which the actor is calibrated; that is, ideal deceleration is perceived as a percentage of the maximum deceleration. Figure 8a shows data from a sample trial with both ideal deceleration (dotted line) and current deceleration (solid line) expressed as a percentage of maximum deceleration.[4] Notice that ideal deceleration always drifts away from current deceleration. When current deceleration exceeds ideal deceleration, ideal deceleration decreases; when current deceleration is less than ideal deceleration, ideal deceleration increases. This happens whenever current and ideal deceleration are expressed in the same units, as they are in Fig. 8a. Hence, if ideal deceleration drifts towards current deceleration, then current and ideal deceleration must be expressed in different units.

Now consider the situation encountered by subjects in Group A of Experiment 1. Immediately following the decrease in brake strength in block #6, they were calibrated to a brake whose strength was 12 m/s^2 (based on their experience during the first five blocks), but the actual brake strength was only 9 m/s^2. If ideal deceleration is always perceived in units of the strength of the brake to which the actor is calibrated, then subjects in this situation would underestimate ideal deceleration by 25%. Thus, if at some moment ideal deceleration happens to be 6 m/s^2, subjects will perceive that it is possible to stop by applying at least 50% of maximum deceleration when, in fact, at least 67% of maximum deceleration is necessary. This is the situation depicted in Fig. 8b approximately 2.4 s into the simulated trial. The actor quickly adjusts the brake to 65% of its maximum displacement (just to be safe). If the actor was properly calibrated, then perceived ideal deceleration (gray dotted line) should decrease. However, it increases; that is, perceived ideal deceleration drifts upward toward actual deceleration. This tells the actor that the brake to which she is calibrated is stronger than the actual brake. Similarly, if ideal deceleration drifts downward toward actual deceleration, then the actor must be calibrated to a brake that is weaker than the actual brake (as experienced by subjects in Group C of Experiment 1; see Fig. 8c). Thus, actors can use the optical consequences of their actions to iteratively adjust calibration until perceived ideal deceleration always drifts away from actual deceleration.

The results of Experiment 2 allow us to rule out the hypothesis that recalibration is based on feedback about the outcome of the trial. However, additional work is needed to further explore the two hypotheses described in this section.

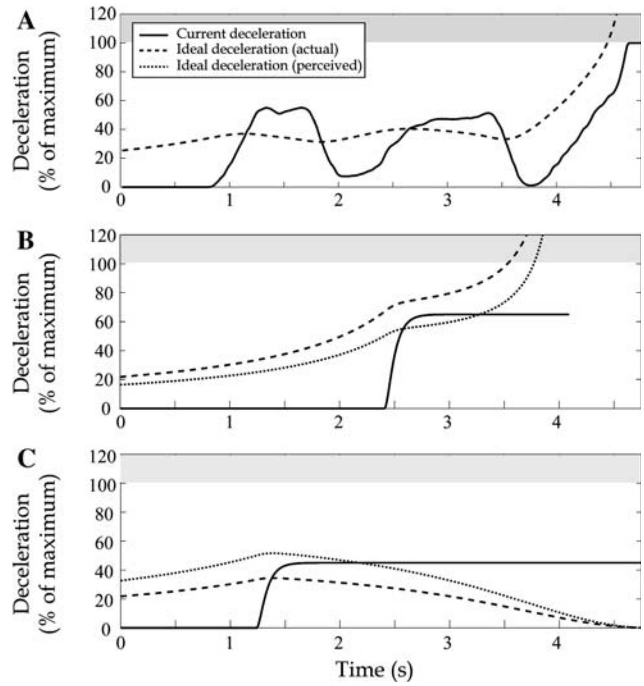

Fig. 8 Data from sample (**a**) and simulated (**b**, **c**) trials showing current (*solid line*), actual ideal deceleration (*black dotted line*), and perceived ideal deceleration (*gray dotted line*)

Outstanding questions about recalibration

The results of the present study address some basic questions about recalibration in the context of continuously controlled visually guided actions. But there are many open questions that were not addressed in this study. First, how precisely do actors know the limits of their action capabilities? Are perceived action boundaries crisp or fuzzy? How does the precision with actors perceive action boundaries change with practice? These are interesting questions considering how precisely the limits of one's action capabilities must be know to perform at peak levels in sports such as cycling, skiing, and race car driving. Second, to what extent does knowledge of action capabilities generalize across tasks? If an outfielder recalibrates to a change in running capabilities while catching fly balls, does this transfer to other tasks that are constrained by running capabilities? Third, how do actors learn how their action capabilities depend on context? Consider, for example, people who routinely drive two vehicles with very different brake dynamics (e.g., a truck driver who spends all day driving a heavy truck that takes a long time to slow down, and then drives home in his small passenger car that can stop quickly). Eventually, the driver may develop two calibration states and rely on contextual cues

[4] The sample trial in Fig. 8a was chosen to illustrate a specific hypothesis about how people could recalibrate on the basis of optical consequences. However, it should be noted that the deceleration profile in Fig. 8a is not typical of the deceleration profiles in most trials, which tended to look more like those in Fig. 5.

to switch between them, circumventing the need for recalibration. Finally, what role do inertial cues play in recalibration? The results of the present study demonstrate that optical information is sufficient for rapid recalibration. However, information in the vestibular and somatosensory consequences of brake adjustments may also be used to recalibrate. Further research on calibration in the context of visually guided action will be necessary to address these questions.

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