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RESEARCH NOTE

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Grip force dynamics in the approach to a collision

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Abstract This experiment investigated the prediction of load force (LF) in impulsive collisions inferred from anticipatory adjustments of grip force (GF) used to stabilise a hand-held object. Subjects used a precision grip to hold the object between thumb and index finger of their right hand and used the arm either: (1) to move the object to *produce* a collision by hitting the lower end of a pendulum, causing it to swing to one of three target angles, or (2) to hold the object still while *receiving* a collision produced by the experimenter releasing the pendulum from one of three angles. Visual feedback of the pendulum's trajectory was available in the production task only. In all conditions, subjects increased GF in advance of the collision. In receiving the collision without advance information, subjects set GF levels to the midrange of the experienced forces. When subjects possessed knowledge about the maximum angle of pendulum swing – either because they were going to produce it or because they were verbally informed – magnitude of the anticipatory-GF magnitude response was scaled to the predicted LF magnitude. Furthermore, GF was scaled to LF with a higher gain when producing compared to receiving the collision. This suggests that updating forward models through a semantic route is not as powerful as when the updating is achieved through the more direct route of dynamic exploration.

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Introduction

When holding an object in a precision grip, grip force (GF) normal to the surface of an object must produce friction sufficient for load forces (LF; e.g. due to gravity or inertia) tangential to the surface of the object. If this condition is not met, the object will tend to slip out of grasp.

When moving an object, inertial forces as well as gravity act upon the object. Such forces depend on the acceleration of the hand. Thus, the greater the acceleration used to move an object, the higher the GF needs to be to stop the object from slipping from grasp. Flanagan and Wing (1995, 1997) showed that GF rises with or slightly before LF and attains its maximum value in synchrony with maximum LF. This demonstrates an anticipatory basis to the adjustments of GF during voluntary movement (for a review, see Wing 1996). In this paper, we consider the case where the velocity of an object's movement is very rapidly decreased by a collision with another object. The force of a collision depends on the mass and velocity of the two objects. In order to maintain a stable hold on one object when it collides with another, an increase in GF related to the force of impact is needed. Consequently, allowance for both the momentum of the system that the subject is controlling (i.e. the limb and held object) as well as the momentum of the other object is required.

To ensure the stability of a hand-held object subject to a collision, there are a number of different possible strategies. A subject might wait and increase GF only in reaction to the impact. In this case, subjects would make use of sensory feedback mechanisms, which can restore stability quickly after a slip has been detected. These triggered responses have been described as being long-latency reflexes, appearing 60–100 ms after impact and scaled to the magnitude of the event (Bennis et al. 1996;

Johansson and Westling 1988b; Lacquaniti and Maioli 1989a). However, these reactive responses might not be the most appropriate way to avoid object-slip. Indeed, in the case where there are appreciable impact forces (as much as 5× the object's weight), the object would probably be projected out of grasp by the time these responses produced their mechanical effect. Another possible strategy would be to over-grip the object to ensure that whatever happens, the increase in LF would be accounted for. This has the disadvantage of being inefficient and possibly inducing muscle fatigue and cramps. A better approach might therefore be to anticipate the magnitude of the collision and prepare the system shortly before the collision occurs.

One important factor in a collision is the momentum associated with each of the two objects at impact. Thus, the goal of the different characteristics of the movement should be directed at the kinetics of the event, i.e. duration and force of impact, which subjects need to anticipate to stop the object from slipping out of grasp. A held object can be involved in a collision in two different ways. Either it can be the moving object that produces the collision; or it can be stationary and be hit by an external body. Previous work has mainly focused on the latter case. Li (1997) showed that the dynamics of a moving ball are taken into account in the control of an interceptive action. Indeed, both hand-movement velocity and amplitude were scaled to the velocity and mass of the moving target and therefore, to the force which was going to be experienced at impact (see also Carnahan et al. 1997; Chieffi 1992). Johansson and Westling (1988b) examined the nature of the compensatory actions that occurred when the load of a test object was rapidly increased by dropping a small ball onto the held-object. GF was scaled to factors affecting the momentum of the dropped ball and thus, an appropriate safety margin was present to prevent slips, even at the crucial period of impact. Similarly, in a catching paradigm, it was shown that the anticipatory EMG responses appeared roughly 100 ms before impact and that the mean amplitude of these responses increased linearly with the expected momentum of the ball at impact (Lacquaniti and Maioli 1989a, 1989b).

Previous experiments showed anticipation based on subjects' appreciation of the effects of gravity and/or of the consequences of an external event that would sharply increase the forces applied to the target limb. The primary interest in the present study was to determine whether GF also provides a good index of subjects' prediction of a collision that they produce themselves. A close scaling of GF with the induced LF would be a good indication that subjects utilised information about the dynamics of the collision. It has been suggested that anticipatory adjustments of GF for LF fluctuations might be based on an internal forward model of effector and object dynamics (Blakemore et al. 1998; Flanagan and Wing 1995). If GF scales with LF in self-produced collisions, it would be of interest to ask whether this would be true of imposed collisions with verbal instruction. Two other conditions were therefore included in order to look at the effects of verbal information on GF/LF relations. Subjects were required to produce a collision (producing task) or receive one (receiving task). In all three conditions, their task was to ensure that the hand-held object did not slip.

Materials and methods

Subjects

Twenty-one right-handed students (13 female, 8 male; aged 18–43 years; mean 25 years) participated in this experiment as part of a course requirement. All subjects were naïve to the experimental objectives and to the test apparatus and gave their informed consent prior to participating in the experiment.

Apparatus

Using their right hand, subjects grasped an object with parallel wood-surfaced sides (width 4.5 cm; weight 250 g) using three fingers on one side and the thumb on the other. A load cell (Novatech Model F245), mounted between the grip surfaces, measured GF produced by the digits normal to the surface. At the beginning of the session, finger positions on the object were outlined and subjects were instructed to reposition the fingers within the prints after each trial. To encourage whole-arm movement, subjects wore a wrist protector that prevented flexion/extension. An accelerometer (Entran EGA-F-25), positioned at the hand-end of the wrist protector, measured hand acceleration in the frontal plane (resolution of 0.005 $m{\cdot}s^{-2}$).

Subjects were seated facing a pendulum (length 1.5 m), which swung in a fronto-parallel plane. Seated on an adjustable chair, they were comfortably positioned so as to have the lower end of the pendulum approximately 40 cm in front of them and 20 cm above waistline. Their task was to use the object to receive or produce a collision with a second load cell (Novatech Model F241), which was located on the lower end of the pendulum. This second load cell, whose contact surface was cushioned with 5-mm-thick high-density foam to reduce collision-induced vibration, was used to record the force of impact (in N) as a measure of the LF applied to the hand-held object at impact. The total weight of the pendulum (i.e. load cell and rod) was 450 g. Pendulum angle was measured with a flexible goniometer (Penny and Gilles, Model Z110). Grip force, hand acceleration, pendulum angle and force of impact were all sampled at 1000 Hz. Signal to noise level was such that no filtering was required.

Experimental procedures

Subjects participated in a single experimental session, lasting 90 min and comprising three conditions. The order in which the conditions were performed was counterbalanced across subjects.

Condition A

Subjects were instructed to produce a collision in each trial by hitting the load cell on the pendulum with the hand-held object (the pendulum was stationary until the collision). Before each trial, the experimenter announced how far the pendulum should swing. This target was set to 5, 15 or 25°. The subjects' task was to send the pendulum within half a degree of the target. A tone sounded to indicate the start of the trial, and subjects, starting 40 cm to the right of the stationary pendulum, were given 3 s to hit it. They were specifically instructed to produce a collision (i.e. short contact) and not to push the pendulum. Trials where the pendulum was pushed were rare (<1%) and immediately rejected. A scale was placed behind the pendulum to provide subjects with direct visual feedback. In addition, at the end of each trial, the experimenter provided verbal feedback on the relative precision of the hit (e.g. „the pendulum swung 2.2° too high“). After each trial, subjects were allowed to relax their grip by placing their hand on the lap if they wished to do so. For this condition, 60 trials (20 trials for each target) were performed. Trials were presented in a cyclic ascending or descending order (i.e. target angles 5, 15, 25, 5 ... or 25, 15, 5, 25 ... degrees).

Conditions B and C

At the beginning of each trial, subjects were asked to place the hand-held object right up against the load cell on the pendulum, which was stationary. When ready, the experimenter raised the pendulum through an angle of 5, 15 or 25°. A tone sounded to indicate the beginning of the trial, and the pendulum was then released to swing down and collide with the hand-held object, 0.5–3 s after the tone had been heard. Subjects were instructed to hold the object so that it would not slip out of their grasp. In order to prevent subjects from seeing the pendulum’s release point and its swing trajectory, a black cloth screen was positioned between subject and pendulum. This screen did not prevent subjects from seeing their arm and hand. In condition B, subjects were told from what angle the pendulum would be released prior to each trial. They went through a series of 30 trials (10 for each release angle), with release angles presented in a cyclic order as in condition A. In condition C, subjects received no information about the release angle. This condition comprised 15 trials, five for each release angle, with the release angles presented in pseudo-random order.

Data processing and analysis

For each condition, the last five trials at each target and release angle were analysed. GF data were differentiated to calculate rate of change of grip force (dGF) and acceleration signals were integrated to obtain hand velocity. Data were then processed and analysed using software that enabled automated scoring of time and magnitude of maximum GF (before and after impact), dGF, velocity of the hand, angle of pendulum swing and force of impact. Analysis of variance (ANOVA) revealed no significant effect of trial or order of conditions. To investigate the effects of the experimental conditions on the scaling of GF to force of impact, the slope of the regression lines for each individual subject and in each experimental condition was calculated across the force range. After averaging the regression coefficients across subjects, the effects of the different experimental conditions were investigated by running paired *t*-tests on the group mean values. Secondly, the effects of condition (A, B, C) and release angle (5, 15, 25°) on pendulum swing, impact force, velocity, acceleration were investigated with a 2-way repeated-measures ANOVA.

Results

Figure 1A is an illustrative trial from condition A. A steady GF baseline of 3.52 N was observed before the start of the trial. After the tone, as the subject moved the hand towards the pendulum, GF level increased and reached a maximum value of 25.4 N, at time of impact[1]. As a result of the collision, the pendulum started to swing and reached the 25° target. On average, subjects’ responses were within 1.6° of target values, with a tendency to overshoot 5 and 15° and undershoot 25° (see Table 1 for a summary of the results). Prior to collision, maximum hand-velocity, averaged over subjects, increased significantly with target angle [$F(2,160)=6.1$, $P<0.01$], resulting in increasing magnitudes of impact forces [$F(2,160)=232.1$, $P<0.01$].

Figure 1B shows a typical trial from condition B. GF was steady at 3 N prior to the tone. Following the auditory signal, a clear increase of GF was seen prior to impact. The impact was followed 70 ms later by a sharp increase in GF. This occurred in a stereotyped pattern on every trial and given the latency, suggested a supraspinal reflex.

An example from condition C is presented in Fig. 1C and revealed a reflex increase in GF at a latency of 74 ms. A small increase in GF was observed prior to impact. However, the size of this anticipatory response was not as large as that seen in Fig. 1B. In conditions B and C, peak hand-velocity prior to collision was not significantly different from zero ($P>0.05$; velocity curves are not shown).

Table 1 Means and standard deviations for maximum values of the measured variables, for each condition and target level. *Anticipatory scaling* and *reactive scaling of grip force* (*GF*) refer to the magnitude of maximum GF measured before and after impact, respectively. *dGF magnitude* and *time* refer to the characteristics of maximum rate of change of GF measured in the reactive response, i.e. after impact, for conditions B and C

Condition	Target (degrees)	Pendulum swing (degrees)	Force of impact (N)	Velocity (m/s)	GF baseline (N)	Anticipatory scaling of GF (N)	Reactive scaling of GF (N)	dGF magnitude (N/s)	dGF time (ms)
A	5	8.1 (1.3)	15.9 (5.8)	0.5 (0.2)	4.3 (1.9)	9.7 (6.0)			
	15	16.0 (1.2)	41.3 (9.8)	0.8 (0.3)	4.9 (1.9)	23.7 (9.1)			
	25	24.7 (1.2)	75.2 (13.5)	1.2 (0.4)	5.7 (2.5)	40.7 (10.6)			
B	5	7.0 (1.0)	6.9 (1.7)		4.1 (2.0)	9.1 (4.5)	11.8 (5.8)	62 (34)	66 (38)
	15	16.5 (0.8)	26.8 (2.8)		4.5 (2.2)	16.5 (7.3)	27.3 (9.7)	210 (103)	74 (36)
	25	26.1 (0.7)	52.4 (3.6)		5.9 (2.2)	23.9 (10.6)	42.1 (13.9)	377 (184)	75 (35)
C	5	7.1 (1.2)	6.9 (1.5)		5.1 (2.3)	15.5 (9.7)	19.2 (9.5)	90 (54)	81 (19)
	15	16.7 (0.8)	27.5 (3.1)		4.9 (2.2)	15.8 (10.7)	26.6 (11.2)	229 (126)	85 (20)
	25	26.4 (1.1)	52.5 (5.2)		4.8 (2.3)	16.7 (13.6)	34.8 (14.6)	337 (138)	87 (23)

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[1] GF modulates right at the beginning of the hand movement as it begins to accelerate towards the pendulum; but this increase is not sufficient to be visible on the scale required to show maximum GF at impact.

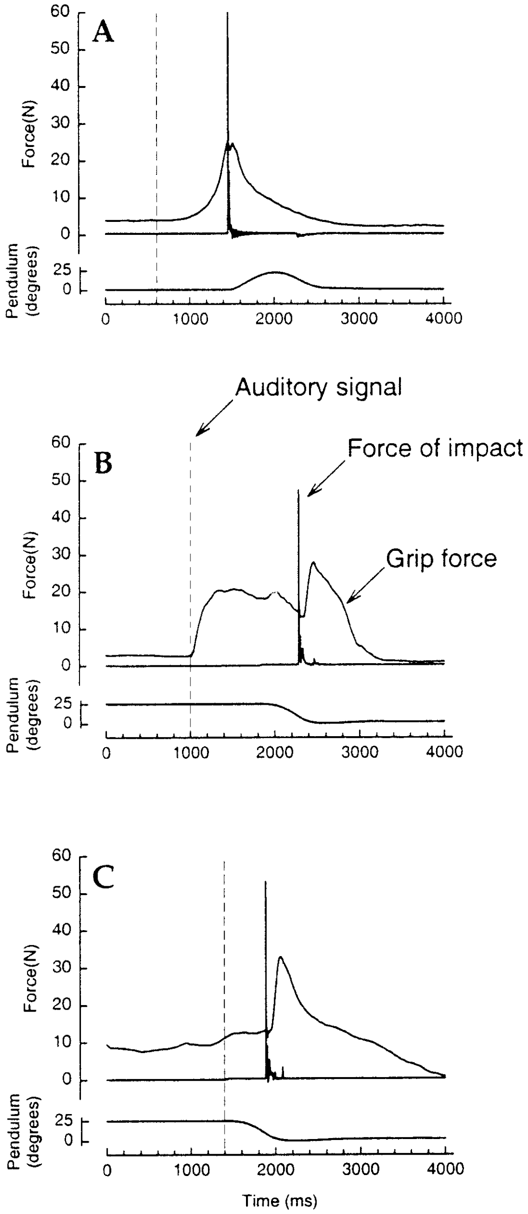

Fig. 1. A Typical trial from the production task A. **B** Example of a trial observed in the receiving task, where the experimenter told subjects what to expect (task B). In the third condition (**C**), subjects received the collision and were not told from what angle the pendulum was released (task C). In all conditions, subjects were instructed to insure that the hand-held object did not slip out of their grasp. In these examples, the maximum angle of pendulum swing was 25°

Grip Force

To determine if initial conditions were constant, GF baseline was measured 1 s prior to the auditory signal at the beginning of the trial. No difference across conditions was found [*F*(2,320)=1.9, *P*>0.05]. To examine the scaling of GF, both in anticipation of and in reaction to the collision, maximum GF was plotted as a function of impact force (see Fig. 2 left for anticipatory responses; right for reactive responses).

In both conditions where subjects had prior information about the collision (i.e. A and B), there was a significant scaling of GF in anticipation of the expected force of impact [*F*(2,160)=48.9, *P*<0.01]. However, the slopes of the regression lines were significantly greater in condition A (+0.50) than in B (+0.27). In Condition C, where no information about the forthcoming collision was available, there was no anticipatory scaling of GF [*F*(2,160)=0.4, *P*>0.05]. The mean slope observed in this condition was +0.03. For all three release angles, mean GF magnitudes were similar to the mean GF observed for the middle release angle 15° of condition B (see Fig. 2 left).

In conditions B and C, but not in A, responses triggered by the impact were observed. In both B and C, the magnitude of these reactive responses was significantly scaled to the force of impact experienced [*F*(2,160)=12.8, *P*<0.01; see Fig. 2 right]. The slopes of these regression lines were significantly different (+0.63 for B; +0.34 for C). However, when allowance was made for the differences observed before impact (Fig. 2 left), no difference was found in the scaling of GF to LF increase between the two conditions (Fig. 2 right). Maximum dGF occurred 65–90 ms after collision. This maximum was significantly earlier in condition B than in C [*F*(1,80)=3.2, *P*<0.05]. There was an increase in the maximum value of dGF with impact force [*F*(2,160)=164.6, *P*<0.01]. However, there was no reliable difference in the mean slope of the regression lines between the two conditions.

Discussion

In a collision between a hand-held object and another object, a load force (LF) much greater than that due to gravity may act for a short period of time on the gripped object. To prevent slip at impact, grip force (GF) must be appropriately increased at or before the collision. This requires anticipation of the dynamics of the forthcoming collision. The focus of the present experiment was to determine whether GF is scaled to different magnitudes of collision. This was investigated this in two different contexts. In condition A, subjects produced the collision by hitting the lower end of a pendulum. Their task was to hit the pendulum to make it swing up to one of three specific targets. In conditions B and C, subjects received a collision while maintaining their arm in a constant location in space with (B) or without (C) prior indication of the magnitude of the impact, which could take three different values, according to the release height of the pendulum.

The results revealed that when subjects produced collisions, shortly before impact, there was a maximum in GF which was scaled to the magnitude of the forthcoming LF due to the impact. This suggests an anticipation of dynamics of the collision. There was also evidence of anticipation when receiving the collision: GF increased before impact. However, only with prior knowledge was this increase scaled to the magnitude of impact and, even then, the scaling was less than when producing the colli-

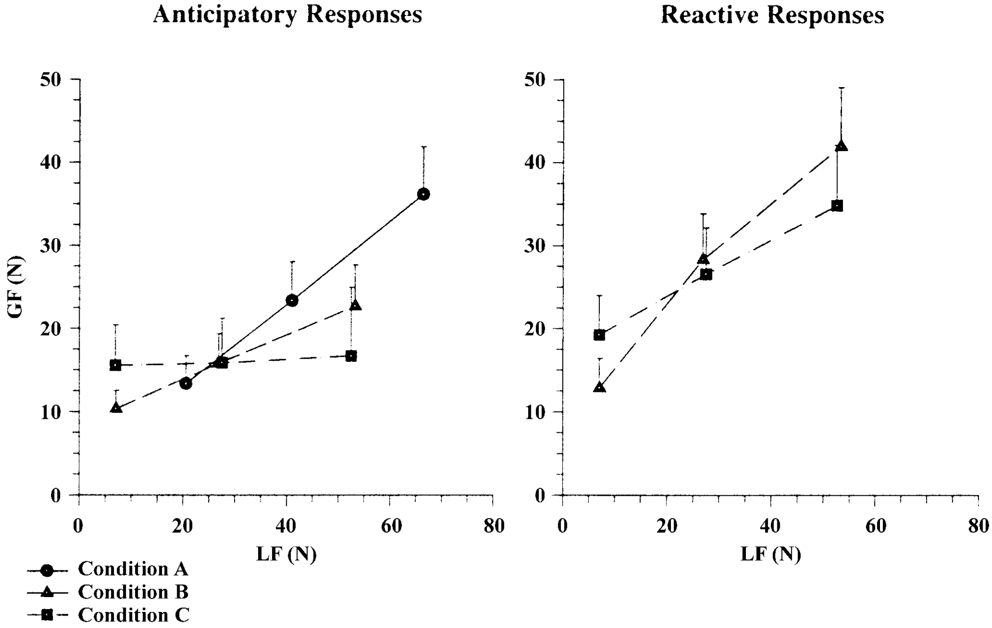

Fig. 2 Regression lines for grip force (*GF*), before (*left*) and after (*right*) collision, are presented for three levels of load force (*LF*) at impact. Values for GF are the means averaged over subjects and the *vertical bars* represent the standard deviations. Results for all three conditions are presented for the anticipatory responses; for the reactive responses, only conditions B and C are presented since no responses were observed in condition A

sion. When subjects were not told the pendulum release angle and, thus, had no indication of what magnitude of collision to expect, GF was scaled to the middle force of the range. For imposed collisions, there was a sharp increase in GF after impact at such a short latency that this increase in GF may be considered to be a reflex triggered by the collision. Triggered responses were scaled with a higher gain and unfolded more rapidly when information about the release angle was given. There was no evidence of any triggered response when subjects produced the collision.

In recent years, there has been an increased interest in the theoretical concept of internal models underlying motor planning. In this viewpoint, internal forward models, which capture the causal relationship between actions and outcomes (Wolpert 1997), are built and updated through the experience of kinematic and/or dynamic transformations of the interactions between our body and the environment (Imamizu et al. 1995). In condition A of the present experiment, subjects were to produce a collision between a hand-held object and a pendulum. At first they did not have any knowledge of the properties of the pendulum. As the session progressed, subjects were able to explore the pendulum's dynamics, which may have enabled them to refine models of not only their limb, but also of the pendulum's dynamic behaviour. In this way, it may be assumed that this is how, by the end of the session, subjects' prediction of the load-force increase due to the self-generated collision was appropriate, as indicated by the tight scaling of GF to the different magnitudes of collision.

In conditions B and C, the collision was imposed on the subject with a magnitude that depended on the release angle of the pendulum as set by the experimenter, i.e. the collision was externally generated. Under this condition, we found a sharp rise of GF within 100 ms after impact. These triggered responses were closely scaled to the force of impact. Similar results were described by Häger-Ross et al. (1996) and Lacquaniti and Maioli (1989b). The latter findings have been further extended by showing that, with verbal information, reactive responses unfolded significantly faster than when subjects were not given the possibility to use feedforward mechanisms. Available information may have been used to preactivate and, thus, facilitate the release of the triggered response (Bennett et al. 1994; Timmann and Horak 1997). However, verbal cueing of the magnitude of a forthcoming collision did not have an effect on the scaling of GF in reactive responses. Consequently, the important point to underline here is that verbal information *did not* have any effect on the magnitude of the triggered responses, but *did* have an influence on the scaling of the anticipatory responses to different magnitudes of collision. Thus, it seems that verbal information about the magnitude of an externally imposed collision can be used to update an internal forward model.

The results presented here clearly demonstrate that, in both conditions A (production task) and B (receiving task), subjects had some knowledge about the dynamics of the two different types of collisions. This knowledge could be used to update internal forward models and, thus, enable subjects to prepare for the forthcoming events (i.e. GF was scaled in anticipation to LF increases in both conditions). However, results showed that GF scaling had a higher gain when subjects were asked to hit the pendulum. This could imply that, in the situation of a self-generated collision, subjects are able to extract more quantitative or qualitative information about the experienced event, which enabled them to anticipate better the next one (Johansson and Cole 1994; Johansson and Westling 1988a; Westling and Johansson 1984). At least two alternatives could be put forward to explain these results. First, it might be the case that the control of the collision in the two contexts involved different goals and different underlying mechanisms. For example, when producing the collision, subjects might have focussed their attention on the target that the pendulum was to reach (i.e. they were focussing on the consequence of their movement). When receiving the impact, subjects may have been more concerned about not letting the object drop. In this case, attention may have been switched to a voluntary monitoring of the force applied through the fingers prior to impact, leading to a less effective anticipatory scaling of GF. A similar concept has been advanced by Wulf et al. (1998) in the context of skiing. Another, and maybe more interesting possibility, is that the updating of internal models through a semantic route is not as powerful as when the updating is achieved through a more direct route (i.e. dynamic exploration). Verbal information may not be sufficient for subjects to establish a precise coupling between the release angle and the sensory feedback experienced in previous collisions. The present paradigm offers a simple, but powerful means of investigating these issues.

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