Effect of Scenario on Perceptual Sensitivity to Errors in Animation

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A deeper understanding of what makes animation perceptually plausible would benefit a number of applications, such as approximate collision detection and goal-directed animation. In a series of psychophysical experiments, we examine how measurements of perceptual sensitivity in realistic physical simulations compare to similar measurements done in more abstract settings. We find that participant tolerance for certain types of errors is significantly higher in a realistic snooker scenario than in the abstract test settings previously used to examine those errors. By contrast, we find tolerance for errors displayed in realistic but more neutral environments was not different from tolerance for those errors in abstract settings. Additionally, we examine the interaction of auditory and visual cues in determining participant sensitivity to spatiotemporal errors in rigid body collisions. We find that participants are predominantly affected by visual cues. Finally, we find that tolerance for spatial gaps during collision events is constant for a wide range of viewing angles if the effect of foreshortening and occlusion caused by the viewing angle is taken into account.

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1. INTRODUCTION

There are several reasons why an animation application might deviate from physically correct rigid body motion, such as computational savings from approximate collision detection [O'Sullivan and Dingliana 2001] or achieving a particular animation result [Barzel et al. 1996]. Deviating too far from physical correctness, however, can lower the perceived naturalness of the animation [O'Sullivan et al. 2003; Reitsma and Pollard 2003]. Furthermore, it has been suggested that the increased realism of modern rendering techniques could additionally constrain the acceptable range of deviations, due to the increased sensitivity of users to more detailed displays [Stappers and Waller 1993] and mismatched quality levels between animation and rendering.

It is unknown, however, whether people tend to be more or less sensitive to errors in more realistic environments. Can particular aspects of a scenario, such as audio or textures, be manipulated in order

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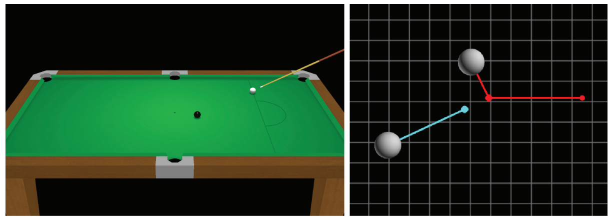

(a) (b)

Fig. 1. (a) our snooker scenario. (b) the test scenario of O'Sullivan et al.

to raise or lower user tolerance to errors in the animation? Or, by contrast, do users typically notice errors in animation regardless of the context offered by a scene?

We examine user sensitivity to angular, spatio-temporal, and physics errors applied to physically simulated rigid body dynamics in a realistic environment (Figure 1(a)). We compare our results to previous studies of similar errors conducted using abstract stimuli (Figure 1(b)), and examine potential causes for the observed differences. In addition, we examine the relative importance of visual and auditory cues for spatiotemporal errors during rigid body collisions.

We find that the choice of scenario used for testing can significantly bias user sensitivity to angular distortions, but that the addition of a high-contrast texture to provide rotational information does not affect user sensitivity to such distortions. Sensitivity to brief delays in the animation at the time of collision appears to be invariant to scenario and to the timing of audio from that collision; indeed, we find no evidence that audio cues affect user sensitivity to any types of errors. Our experiments indicate that localized errors that can be directly observed tend to be unaffected by the choice of scenario, whereas more global errors whose presence must be inferred from the overall motion of an object tend to be significantly affected by scenario appearance. Finally, we find that the overhead view used in many experiments results in equivalent or more conservative error tolerance thresholds than alternative viewing angles, and user sensitivity appears to change slowly with modest deviations from the overhead angle.

2. BACKGROUND

A number of researchers have suggested techniques for exploiting approximate physics in animations, especially approximate collisions. O'Sullivan and Dingliana [2001] examined perceptual thresholds for approximating collisions to reduce computational complexity, while Barzel et al. [1996], Chenney and Forsyth [2000], Popović et al. [2000], and Twigg and James [2007] used approximate collisions to achieve plausible goal-directed animations. One of our goals is to provide guidance on perceptual sensitivity to various types of errors in order to allow tools such as these to be used more effectively.

The interactions of a small number of simple objects have been studied for decades [Michotte 1963; Cohen 1964; Stappers and Waller 1993; Kaiser and Proffitt 1987; O'Sullivan and Dingliana 2001; O'Sullivan et al. 2003]. We draw on the experiments of Kaiser and Proffitt [1987] and O'Sullivan et al.[2003] as the starting point for our experiments. Kaiser and Proffitt examined user sensitivity to a variety of errors applied to the collision of two circular bodies in an abstract 2D environment, and included a simple model of friction (constant deceleration) in their experiments. O'Sullivan et al. extended the examination of these errors to an abstract 3D environment but did not consider friction. We examine sensitivity to these errors in a physical simulator, providing a visually realistic environment with physically correct dynamics.

Research has demonstrated increased user sensitivity to motion displayed on richer and more detailed models, including a fountain with varying numbers of water droplets [Stappers and Waller 1993] and more or less realistic humanoid characters [Hodgins et al. 1998]. Similarly, Oesker et al. [2000] reported more detailed and realistic animation of humanoid football players resulted in more accurate user discrimination of relative skill. We examine whether there is a similar link between realism or detail and user sensitivity in the case of rigid body animation errors.

Recent multimodal perceptual research shows that visual and auditory motion cues can potentially interact. Alais and Burr [2004] report a small increase in sensitivity to bimodal motion (i.e., simultaneous apparent motion of a sound source and visual stimulus) but no directional effect (i.e., visual and auditory motion in the same direction is no more detectable than visual and auditory motion in opposite directions). Their results suggest that visual and auditory cues may be processed independently and then combined at the participant's decision stage. However, auditory and visual cues can also interfere in some contexts. The Metzger illusion [Metzger 1934] involves two dots, one moving left to right and the other moving right to left along the same level. When the two dots meet, their interaction is ambiguous, as they could be perceived as either bouncing off or passing through each other; however, an auditory cue played at the moment the balls touch results in a consistent perception that the balls are bouncing off of each other [Sekular et al. 1997]. McGurk and MacDonald [1976] found that given a video of a person saying one phoneme that had been dubbed over with a different phoneme, participants perceived a third phoneme intermediate between those presented by the two stimuli. Accordingly, we investigate whether a similar multimodal interference occurs in the perception of spatiotemporal errors in animated motion.

An earlier version of this article appeared as Reitsma and O'Sullivan [2008]. The primary addition in this version is the fourth study, which tests the hypothesis that error locality modulates scenario effect on user sensitivity.

3. EXPERIMENTAL SETUP

As the testbed for our experiments, we use a physically simulated snooker environment (Figure 2(a)). A full 3D physics engine was used to correctly compute the inertial tensors of the simulated bodies, allowing us to cleanly and correctly make changes to any aspect of the motion of the simulated balls. Physical constants were set to give the most realistic appearance to behaviour in the original simulator (see Table I) and were not changed for our experiments.

We selected snooker as the subject of the simulation primarily due to its innate similarity to the abstract environments used in many previous experiments. Additionally, however, snooker has the benefit of being a familiar and easily understood scenario, which we surmised would help strengthen the sense of realism we wished to examine.

For all experiments, ball placement was handled identically, with most aspects randomized in order to prevent systematic bias. For each experiment, a target pocket was selected uniformly at random. The target ball was placed on the circle with radius 65cm from the centre of the pocket, with a randomly chosen angle determining its location on this circle. An angle of 0 degrees resulted in the target ball being placed on the centre line of the pocket (i.e., equidistant between the two cushions on either side of the pocket). The angle was chosen uniformly at random in the range between -15 degrees and $+15$ degrees for corner pockets and in the range between -20 degrees and $+20$ degrees for side pockets so as to prevent the ball's trajectory from being at too shallow of an angle with respect to the sides of the table. Furthermore, the placement was determined such that there was a 50% chance each of the ball sinking into the pocket or missing by a random angle up to 10 degrees. The cueball was then placed 65cm from the target ball, with its angle randomly chosen such that it would strike the target ball from either left or right (as chosen) at a 20- to 40-degree angle, and such that the target ball would

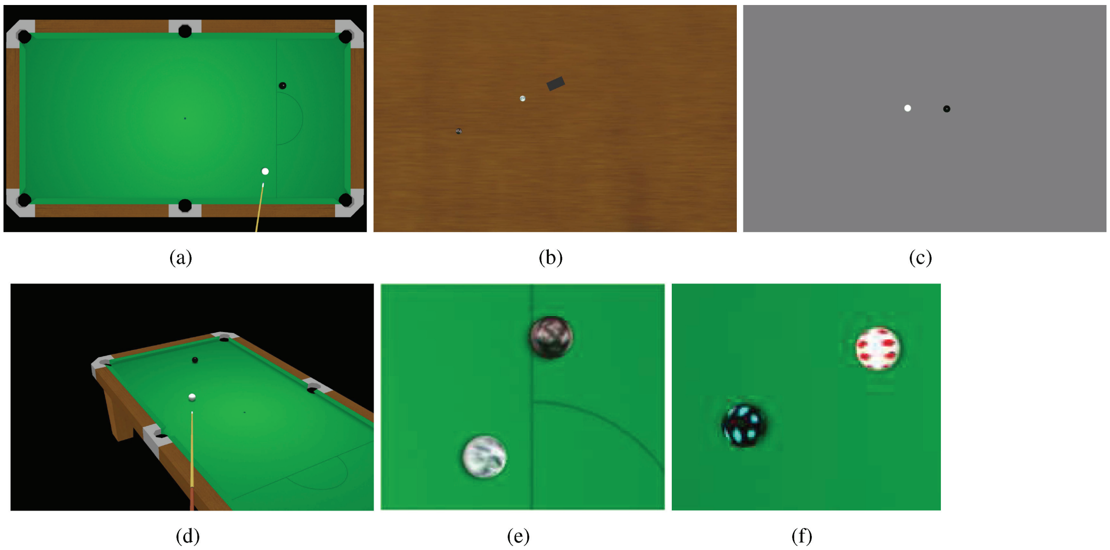

Fig. 2. Test environments used in our experiments. (a) base snooker scenario. Cueball is white, target ball is black. (b) the nonsnooker environment used in Experiment 2. (c) the neutral environment used in Experiments 3 and 4. (d) the snooker environment seen from a 60° angle. (e) a close-up of the texture applied to the balls in Experiment 2. (f) a close-up of the texture applied to the balls in Experiments 3 and 4.

Table I. Physical Constants Used in the Simulator. COR Stands for Coefficient of Restitution, and Angular Friction is for Spinning Around the Vertical Axis

Physical Constant	Value
Ball Sliding Friction	0.25
Ball Rolling Friction	0.008
Ball Angular Friction	0.002
Ball-Cushion COR	0.95
Ball-Ball COR	0.96
Ball-Cushion Static Friction	0.2
Ball-Cushion Dynamic Friction	0.31
Ball-Ball Static Friction	0.04
Ball-Ball Dynamic Friction	0.0556

follow its prescribed trajectory. (No effects of target pocket, left/right side of table, or top/bottom of table were found for our experiments.) There was one exception to this ball placement system: In the final experiment, the target ball was placed 195cm from the pocket in order to allow equal viewing times for both conditions; in order to allow this longer distance, only the corner pockets were used for this experiment.

The simulation started with both balls at rest. A short animation of a cue (or other striking object in the nonsnooker scenario) withdrawing and then contacting the cueball was followed by the cueball accelerating to a velocity of 1.8m/s, after which all further motion was physically simulated. Simulation was terminated 2s after the first collision between the balls, at which point a response screen was overlaid.

The stimuli were shown on a 51cm by 32cm display. participants sat approximately 90cm from the screen, so the display occupied approximately 32 degrees of their visual field. A regulation snooker

table (3.6m plus sides) extended across the width of the screen, meaning 1cm of screen distance corresponded to approximately 7.6 cm of simulation distance, and 12cm of simulation distance corresponded to approximately 1 degree of visual field. Each snooker ball had a diameter of 1.0cm on the screen. Participants wore headphones, and were instructed that in some instances the simulation included audio. Participants were instructed to take into account all information from the simulation to determine whether the event was realistic or whether an error was present. Responses were registered by using the left and right index finger triggers of a gamepad to select "yes" or "no" when prompted by on-screen cues.

4. STUDY 1: EFFECT OF SCENARIO REALISM ON USER SENSITIVITY

Our first study examined user sensitivity to postcollision angular distortions in our snooker simulator (Figure 2(a)). We examined four cases:

(1) Expansion of target ball postcollision angle, clockwise.
(2) Expansion of target ball postcollision angle, counterclockwise.
(3) Expansion of cueball postcollision angle, clockwise.
(4) Expansion of cueball postcollision angle, counterclockwise.

Our hypothesis was that the results would not differ from those reported by O'Sullivan et al [2003].

Each of these cases was evaluated using randomly interleaved ascending and descending staircases [Cornsweet 1962; Levitt 1971] with eight reversals. Staircase methods are adaptive tests which rapidly home in on a participant's perceptual threshold, which can improve the efficiency of studies. In addition, combining ascending and descending staircases helps to avoid misinterpreting results due to guessing, as near-random responses will tend to result in the ascending staircase converging to a substantially lower value than the descending staircase, indicating low reliability.

Alterations to the postcollision angle of the cueball and the target ball were presented in separate blocks, for a total of two blocks of four staircases each. A cumulative normal distribution function (ogive) was fitted to the responses of each participant for each of the four experimental conditions, allowing the participant's point of subjective equality (PSE; the error magnitude at which they would be 50% likely to consider a motion as having an error) and just noticeable difference (JND; the difference between the error magnitudes required to elicit 50% and 75% rejection rates) to be computed. Added errors were capped at 120 degrees in order to prevent wrapping around 360 degrees or settling into local minima, and participants who persistently responded that motions with maximum error were realistic were assigned a value of 120 degrees for that error condition.

There were 19 volunteers in this study: 14 male and 5 female staff and students, aged 13 to 46 (mean 27). All participants had normal or corrected-to-normal vision, were naïve as as to the types of errors being examined, and were given the same set of instructions.

4.1 Results

The results of these experiments are shown in Table II. Throughout, we applied (uncorrected) t-tests for between-study comparisons and paired t-tests for within-study comparisons. As in the simpler and less realistic scenario of O'Sullivan et al. [2003], no difference was found between clockwise and counterclockwise expansion; however, participants were in general more tolerant of errors in our experiment. Our mean PSE for the target ball was $46.5^\circ \pm 2.5^\circ$, as compared to 30° found by O'Sullivan et al. Similarly, our mean PSE for the cueball was $85.4^\circ \pm 5.3^\circ$, which again differs substantially from O'Sullivan et al.'s mean PSE for the striking ball of 60°.

Insight into this difference can be gleaned from poststudy responses and from the pattern of results for which staircase convergence was poor. Some participants, typically those who rated their familiarity

Table II. Results for Our First Study
Point of Subjective Equality (PSE) is the magnitude of error where a participant was 50% likely to notice and remark on it. Just Noticeable Difference (JND) is the additional magnitude of error required to change from 50% to 75% rejection threshold. Values are given as mean ± Standard Error of the Mean (SEM).

Ball	Direction	Mean PSE	Mean JND
Target	Clockwise	$46.7^\circ \pm 3.4^\circ$	$16.9^\circ \pm 4.0^\circ$
Target	CCW	$46.4^\circ \pm 3.8^\circ$	$17.4^\circ \pm 3.8^\circ$
Cueball	Clockwise	$82.8^\circ \pm 6.8^\circ$	$57.7^\circ \pm 11.7^\circ$
Cueball	CCW	$88.1^\circ \pm 8.2^\circ$	$58.0^\circ \pm 11.2^\circ$

with snooker as high on the poststudy questionnaire, reported that some of the collisions they saw were possible, but only with high levels of spin on the cueball; some even reported that they had been strongly influenced by their belief that they could personally have made many of those shots.

Similarly, while most data was well-approximated by an ogive, there were two characteristic types of nonconvergence. The first is when the ascending and descending staircases for a particular error condition converged to different values; the second is when a participant consistently answered "realistic" to motions with maximum error, and hence did not converge to a fixed value. While 6 of 11 participants who reported low experience with snooker had the first type of nonconvergence on one or both cueball error treatments, none of the 8 participants who reported high experience with snooker converged to two different values in that manner. In contrast, none of the 11 low-experience participants failed to converge in the second manner, whereas 3 of 8 high-experience participants had type 2 nonconvergence. This distribution is statistically significant ($\chi^2 = 12.0$, $P = 0.0025$), suggesting that the context evoked by a realistic scenario can strongly affect the responses of a participant, and that this effect might explain the lower sensitivity to errors seen in our experiment as compared to O'Sullivan et al. However, other differences between the scenarios (ball size and velocity, presence of friction, etc.) might also account for the difference.

In addition, we examined the data for indications of systematic participant bias toward scenario conditions which were randomly determined (i.e., direction of travel, whether the target ball was successfully knocked into the pocket it was aimed toward, etc.). One bias was found: There was a small but significant decrease in participant tolerance for error when the target ball was successfully knocked into the pocket ($t(20) = 2.58$, $P = 0.018$). The cause of this bias is unknown; however, one possibility is that participants found it jarring how balls vanished when they went into a pocket, rather than continuing to be animated in a physically realistic manner. Another task-related explanation is that people are good at predicting whether their actions in the game will succeed or fail (i.e., miss the pocket). If the distortion results in a success that they were not predicting, they may have a lower tolerance for the error that produced this unexpected outcome. However, further tests would be necessary to examine this intriguing hypothesis. While we do not believe that this minor bias will have skewed any of our other results, as each one is based on hundreds of trials with each of these two conditions, this result does underscore the importance of examining the effect on participant responses of how a scenario is portrayed.

5. STUDY 2: EFFECT OF SCENARIO CONTEXT AND AUDIO CUES

The goal of our second study was to explore the potential for a scenario to provide context that would bias a participant's expectations and hence their tolerance for errors. When examining the effect of

Table III. Results for our Scenario Effect Study
Point of Subjective Equality (PSE) is the magnitude of error where a participant was 50% likely to notice and remark on it. Just Noticeable Difference (JND) is the additional magnitude of error required to change from 50% to 75% rejection threshold. Values are given as mean ± Standard Error of the Mean (SEM). Gap distances are given in terms of on-screen distance; 16mm is approximately 1 degree of a participant's field of view.

Error	Scenario	Mean PSE	Mean JND
Gap	Snooker	5.18mm $\pm$ 0.73	2.29mm $\pm$ 0.78
	Non-snooker	5.79mm $\pm$ 0.88	3.94mm $\pm$ 0.92
Cueball	Snooker	$87.5^\circ \pm 10.4^\circ$	$40.4^\circ \pm 8.3^\circ$
	Non-snooker	$53.1^\circ \pm 12.2^\circ$	$47.5^\circ \pm 12.8^\circ$
Target	Snooker	$39.4^\circ \pm 4.9^\circ$	$14.5^\circ \pm 4.0^\circ$
	Non-snooker	$33.6^\circ \pm 4.6^\circ$	$13.7^\circ \pm 2.9^\circ$

scenario and realism, a natural question was what effect the additional information and verisimilitude provided by realistic audio cues would have. Our hypotheses were:

—Participants would be more tolerant of errors in a realistic snooker scenario.

—Audio cues would lower participant tolerance of errors in general but would raise tolerance if the audio and visual cues conflicted.

There were 16 volunteers in this study: 13 male and 3 female staff and students, aged 20 to 37 (mean 26). All participants had normal or corrected-to-normal vision, were naïve as to the types of errors being examined, and were given the same set of instructions with the added instruction that they were to judge the simulation on its own merits, rather than trying to second-guess whether something they noticed was intentional or not. This additional instruction was added after some participants in pretests reported that they consistently ignored delay errors that they knew were present, under the assumption that such errors were not intended to be part of the test. Trials were presented in random order.

5.1 Scenario Effect on Tolerance

In order to test our hypothesis that participants' sensitivity to errors was being affected by preconceived ideas regarding snooker, we prepared a second scenario (Figure 2(b)) that used identical motion and viewpoint as the snooker scenario but was rendered to look like marble spheres rolling on a wooden plane rather than being a snooker game.

We tested gap errors as well as angular distortion errors in these two environments in order to see if the effects applied to different types of errors. A gap error resulted in the first collision between the two balls occurring as if the cueball had its radius increased by the magnitude of the error (i.e., the collision occurred while there still visually appeared to be a gap between the balls).

Angular distortion errors were presented as in the first experiment, and both types were evaluated using matched ascending and descending staircases. Maximum error value for gap errors was 250mm of physical distance in the simulation, which corresponded to approximately 33mm of distance on the participant's screen. Balls were given identical textures in all error conditions.

5.1.1 *Results.* Table III shows the result of scenario on tolerance for error. The main result is that scenario had a strong effect on participant tolerance for some types of errors.

Participants' tolerance for angular errors in the non-snooker scenario was substantially lower than in the snooker scenario (cueball: paired-$t = 2.46$, $P = 0.02$; target ball: paired-$t = 1.73$, $P = 0.05$), and

Table IV. Results for Our Audio Cue Study

Note that data for angular distortions with no audio is from Study 1. Point of Subjective Equality (PSE) is the magnitude of error where a participant was 50% likely to notice and remark on it. Just Noticeable Difference (JND) is the additional magnitude of error required to change from 50% to 75% rejection threshold. Values are given as Mean ± Standard Error of the Mean (SEM). Gap distances are given in terms of on-screen distance; 16mm is approximately 1 degree of a participant's field of view.

Error	Sound	Mean PSE	Mean JND
Delay	Silent	62.0ms ± 10.5	28.2ms ± 9.6
	Early	62.1ms ± 9.4	30.8ms ± 7.7
	Late	62.7ms ± 10.8	39.3ms ± 13.8
	Sound	61.1ms ± 42.6	120.5ms ± 122.5
Gap	Silent	6.17mm ± 0.73	2.15mm ± 0.54
	Audio	6.49mm ± 0.75	2.17mm ± 0.35
Angle	Audio	46.0° ± 5.9	12.4° ± 2.4
	Silent	46.5° ± 3.6	17.1° ± 3.9

was not substantially different from the values reported in the work of O'Sullivan et al. [2003] (cueball: $53^\circ \pm 12^\circ$ vs. 60°; target ball: $34^\circ \pm 5^\circ$ vs. 35°).

In contrast, there was no difference in participant tolerance to gap errors in the snooker vs. non-snooker scenarios (5.2mm ± 0.7mm vs. 5.8mm ± 0.9mm). While participants were more tolerant of gap errors in our experiment than in O'Sullivan et al. (mean PSE 5.5mm vs. 0.7mm), the differing size and speed of the objects makes it impossible to compare the tasks directly.

5.2 Effect of Audio Cues

Realistic audio cues were added to the simulation for collision events (cue/ball, ball/ball, ball/sidewall, and ball/pocket). Our hypothesis was that the additional information given by audio cues would increase participant sensitivity to gap and angular distortion errors. In addition, we examined whether user perception of delay errors could be altered by playing audio cues before the delay or after the delay. A delay error of N ms caused the simulation to pause for the indicated duration the moment the two balls touched for the first time. For trials where audio output was enabled, the sound of the collision was played either before pausing the simulation, referred to as early delay, or after the end of the pause (late delay). Finally, we examined the case where the animation was not paused at all, but the sound of collision was delayed (sound delay). We hypothesized that this would have a similar effect on perceived realism as a delay in the animation. Maximum error value was 250ms for the early and late delay cases and 500ms for sound delay.

5.2.1 *Results.* Table IV shows the results of this experiment. We found that audio cues had no effect on participant sensitivity.

Participants attended almost exclusively to visual cues, and audio cues had no significant effect on any error treatment. In particular, there was no effect on participant sensitivity to delay errors regardless of whether the collision sound was played early, late, or not at all. Moreover, data for the majority of participants did not converge well for the "sound delay" error condition, suggesting they were not significantly attending to the audio cue. Table IV reports data on the "sound delay" error condition only for those participants whose data converged well, the effects of which are considered in Section 8.

We note also that participant tolerance of delay errors did not differ between our study and prior work (mean PSE 62ms vs. 60ms).

6. STUDY 3: CHARACTERIZING USER SENSITIVITY

Our goal for the third experiment was to examine the scenario effect in greater detail by using a different study design. In particular, we wanted to examine whether response bias played a role in the observed differences in participant tolerance for errors between scenarios.

Additionally, prior work and pretests of our own had shown that participant tolerance for gap errors increases as viewing angle from the vertical increases. For a fixed size of gap, however, the visible gap, or apparent size of the physical gap, decreases with increased viewing angle, both due to foreshortening and due to occlusion by the nearer ball, and it would be useful to know whether this quantity accurately predicts participant tolerance for gap errors.

Our hypotheses were:

- Participants would have lower sensitivity to errors in the snooker environment than in a more abstract environment.
- Balls with high-contrast textures would lower participant tolerance to angular distortions.
- Participant tolerance to gap errors at different viewing angles is determined by the visible gap at that angle.

There were 15 volunteers in this study: 10 male and 5 female staff and students, aged 19 to 43 (mean 25). All participants had normal or corrected-to-normal vision, were naïve as to the types of errors being examined, and were given the same set of instructions as for the previous experiments, including the instruction to not second-guess which observations were intended to be part of the experiment.

6.1 Scenario and Texture

Angular distortions to the target ball were tested in the snooker scenario (Figure 2(a)) and in a frictionless neutral scenario (Figure 2(c)), with the neutral scenario appearing first in order to prevent participants from associating it with snooker. Initial velocity in the frictionless scenario was lowered in order to make postcollision velocities similar between the two scenarios.

In order to evaluate the scenarios for participant bias, we adopted a repeated measures design, which allowed a detection-theoretic analysis to be performed. As noted by Reitsma and Pollard [2003], detection theory [Macmillan and Creelman 1991] can be used to derive a bias-independent measure of a user's ability to detect errors in an animated motion. The method takes into account the difference between how frequently the subject correctly labelled a motion as containing an error (hit rate H) and how frequently the subject incorrectly labelled an unchanged motion as containing an error (false alarm rate F). A subject's sensitivity (d) to errors iscomputed as:

$$d = z(H) - z(F) \tag{1}$$

where z is the inverse of the normal distribution function. For example, a hit rate of 50% and a false alarm rate of 16% corresponds to a sensitivity of 1.0, as does a hit rate of 30% coupled with a false alarm rate of 6%. These two examples of how to obtain a sensitivity of 1.0 demonstrate the bias-independent nature of detection theory: As sensitivity is computed based on the relative distribution of the participant's responses rather than on the raw distribution, factors that will systematically bias the responses, such as participant reaction to the level of realism with which the scenario is rendered, are automatically factored out.

Five levels of angular distortion (15° to 75°) were added to collisions, with each error treatment being repeated three times. As our first experiment confirmed that direction (clockwise/counterclockwise) of angular distortion had no effect on participant ability to perceive those distortions, all angular distortions were added in the clockwise direction. Identical collisions without distortion were added to

Table V. Aggregate Participant Sensitivities to Angular Distortion Errors in Experiment 3

Base denotes trials where the snooker balls had their normal appearance, while *Dots* denotes trials where the snooker balls had a dot texture applied, as in Figure 2(f). Sensitivity was highest in the most realistic scenarios, and lowest in the least realistic.

Angular Distortion	Aggregate Sensitivity: Snooker Environ Base	Snooker Environ Dots	Neutral Environ Base	Neutral Environ Dots
0°	0	0	0	0
15°	0.53	0.04	−0.32	−0.25
30°	0.98	0.64	0.92	0.61
45°	1.64	1.56	1.65	1.25
60°	2.45	2.29	2.15	1.73
75°	3.43	2.73	2.44	2.19

balance, resulting in a total of 30 motions. Each of these motions was displayed with the balls textured to appear as a snooker ball or as in Figure 2(f), for a total of 60 trials per scenario. As well as computing sensitivity measures per participant and in aggregate, PSEs and JNDs were computed in the same manner as for previous experiments.

6.1.1 *Results.* Table V contains the sensitivity results for this study. We note the surprising result that sensitivity was negative for small angular distortions in the neutral environment, suggesting that participants actually preferred slightly expanded collision angles to fully realistic ones.

We found that participant PSEs for angular distortion were again lower in the neutral environment than in the snooker environment, and by approximately the same amount as with the previous experiment ($35.6^\circ \pm 3.0^\circ$ vs. $43.8^\circ \pm 4.4^\circ$ for the nontextured balls), although the difference was only weakly significant (paired-t = 1.64, P = 0.07). Participants were much more likely, however, to flag a motion as containing an error in the neutral environment (unbalanced ANOVA F(1,1498) = 14.8, $P < 0.001$). This response bias resulted in nearly triple the false alarm rate in the neutral environment as in the snooker environment (15.6% vs. 5.4%), leading to the unusual situation in which participants were both more tolerant and more sensitive in the snooker environment (mean sensitivity 1.23 ± 0.13 vs. 1.46 ± 0.11).

Contrary to our expectations, we found that texture had no significant effect on participant PSEs or on tendency to report that a motion contained an error. We did find that the textures resulted in slightly lower participant sensitivity to errors (1.25 ± 0.12 vs. 1.45 ± 0.12, paired-t = 2.80, P = 0.01) due to a higher false alarm rate (11.7% vs. 8.8% with no textures; hit rate was 47.5% and 45.6%, respectively).

6.2 Visible Gap

Figure 2(a) shows an overhead view of two snooker balls 650mm apart, and Figure 2(d) shows an identical physical distance between two snooker balls as seen from a viewpoint along the cue at a 60° angle to the vertical. Due to the differing viewpoints, the same size of physical gap results in a difference visible gap between the two balls.

For an observer looking along the line between the centres of the two balls a viewing angle which is θ degrees from the vertical (overhead position), a physical distance d between the two balls will result in a visible gap between them of:

$$V = cos(\theta) * d - r * (sin(\theta)tan(\theta) - 1 + cos(\theta)) \tag{2}$$

Table VI. Mean PSE Values for Detection of Gap Errors at Different Viewing Angles from the Vertical, Along with the Amount of Gap Visible at That Angle

Values are given as mean ± Standard Error of the Mean (SEM). Gap distances are given in terms of on-screen distance; 16mm is approximately 1 degree of a participant's field of view.

Viewing Angle	PSE for Physical Gap (mm)	PSE for Visible Gap (mm)
0°	6.39 ± 0.98	6.39 ± 0.98
20°	7.44 ± 1.08	6.76 ± 1.01
40°	9.38 ± 1.33	6.12 ± 1.02
60°	12.17 ± 1.38	2.59 ± 0.69
80°	21.58 ± 1.76	0

where r, the radius of the balls, is 26.25mm. At a 60° viewing angle, a 650mm physical gap corresponds to a visible gap of 298.75mm, a reduction of 54%. These distances in the simulation correspond to approximately 87mm and 40mm, respectively, on the screen used to conduct the experiment. Note that this gives a slightly conservative estimate for visible gap, as our viewpoints were aligned with the cue, which was offset by approximately 1° from the line between the centres of the balls. For our experiment, the difference was around 1%.

Five viewing angles were examined, from 0° (corresponding to the default overhead view; Figure 2(a)) to 80° (corresponding to a view along and just above the cue; Figure 2(d)). Distance from the point of collision was the same for all viewing angles, and the PSE for each viewing angle was estimated as the average of the last four reversals of a descending staircase (out of eight).

6.2.1 *Results.* PSE for visible gap stayed nearly constant for moderate viewing angles (see Table VI), as the physical distance between balls corresponding to the mean PSE increased just fast enough to offset the manner in which increased viewing angle appears to reduce that distance. At steep viewing angles, however, participants detected gap errors with much lower visible gaps.

7. STUDY 4: INTERACTION BETWEEN ERROR LOCALITY AND SCENARIO ON USER SENSITIVITY

Results from studies 1 through 3 indicated that the choice of scenario has a significant effect on user sensitivity, but only for some types of errors. Moreover, we note that a similar effect of scenario appearance on user sensitivity has been seen in other contexts (e.g., Reitsma et al. [2008]), suggesting there may be a consistent pattern affecting which types of errors are affected. We hypothesize that errors that are local in nature and detected by direct observation would tend to be less affected than errors that are more global in nature, and that are more commonly detected by inference from their effect on the overall character of the motion than by direct observation. An example of a local error is the gap errors examined in the third study, as such a gap can be directly observed at the moment of collision, but there are few or no effects of the error after that moment. An example of a global error is the angular distortion errors examined in the first study, as there is no instant or short period of time containing a visible error that can be pointed to, but rather the whole of the postcollision motion evolves in a noticeably incorrect manner.

In order to test this hypothesis, we tested errors analogous to those of Reitsma et al. [2008] in our scenario:

—*Acceleration*: A constant forward acceleration was applied to the target ball from the moment of first collision with the cueball until the end of the simulation. This is a global error.

—*Velocity Spike*: An additional amount of forward velocity was smoothly added to the target ball over a period of 0.1s, starting 0.2s after first collision with the cueball. This additional velocity was maintained for 0.1s, and then smoothly removed over 0.1s. This is a local error.

In our previous experiments, global errors (angular distortion) were affected by scenario appearance, while local errors (spatiotemporal gaps) were not. Additionally, while the presence or absence of a high-contrast texture had no affect on either type of error previously, it is possible that it will highlight changes in linear velocity. Accordingly, our hypotheses were:

—Participants would have a higher tolerance for acceleration errors in the snooker environment than in a more abstract environment.

—There would be no difference in participant sensitivity to velocity spike errors between the two environments.

—The presence or absence of a high-contrast texture on the balls would have no effect on participant sensitivity to any errors.

Accordingly, we tested three scenarios:

—*Snooker*: Basic snooker environment, as in Figure 2(a).

—*Abstract*: Neutral environment from study 3, as in Figure 2(c).

—*Textured*: The Abstract environment, but with the high-contrast texture from Figure 2(e) applied to the snooker balls.

In order to minimize the effects of fatigue on responses, participants were divided into two groups. Group A saw both types of errors in each of the Snooker and the Abstract environments, while Group B saw both types of errors in each of the Snooker and Textured environments. There were 26 volunteers in this study (15 male, 11 female), with 10 participants in Group A and 16 participants in Group B. All participants had normal or corrected-to-normal vision, were naïve as to the types of errors being examined, and were given the same set of instructions as for the previous experiments, including the instruction to not second-guess which observations were intended to be part of the experiment. Trials were presented using the same experimental setup and methodology as the previous studies, with the exception that the scene was animated for slightly less time (0.5s less), and the target ball missed the pocket it was aimed at in all cases (rather than a 50% chance). These changes were made in order to ensure equal viewing time for all trials.

7.1 Results

Study data was analyzed using two-tailed paired t-tests on the data within each group; the exception was for comparisons between the texture and no-texture conditions, which were analyzed using two-tailed unpaired t-tests. If either of a participant's pairs of ascending and descending staircases for an error type failed to converge, we excluded all of that participant's data for that error type, due to the low reliability evidenced by the convergence failure. Accordingly, six acceleration datasets and two velocity spike datasets were excluded based on this measure of reliability. Participant tolerance for errors in the Snooker scenario did not differ between groups (acceleration: $t(17) = 0.68$, $P = 0.51$; velocity: $t(22) = 0.13$, $P = 0.90$), so data for the Snooker scenario was pooled for Table VII.

As hypothesized, participant tolerance for erroneous acceleration (the global error type) was significantly higher in the Snooker scenario than in the Abstract scenario (paired-$t(6) = 5.7$, $P = 0.0012$), and participant tolerance for velocity spikes (the local error type) stayed approximately constant between the two scenarios (paired-$t(8) = 0.23$, $P = 0.82$). The addition of a high-contrast texture resulted in a significant and unexpected increase in participant tolerance of velocity spike errors ($t(22) = 2.89$,

Table VII. Results for Our Fourth Study
Point of Subjective Equality (PSE) is the magnitude of error where a participant was 50% likely to notice and remark on it. Just Noticeable Difference (JND) is the additional magnitude of error required to change from 50% to 75% rejection threshold. Values are given as mean ± Standard Error of the Mean (SEM), and are in centimetres per second (velocity spikes) or centimeters per second (per second acceleration).

Error	Scenario	Mean PSE	Mean JND
Acceleration	Snooker	87 ± 7.4cm/s	56 ± 7.6cm/s
Acceleration	Abstract	60 ± 12.7cm/s	60 ± 9.8cm/s
Acceleration	Textured	63 ± 7.4cm/s	31 ± 7.6cm/s
Velocity	Snooker	47 ± 2.9cm/s^2	31 ± 5.1cm/s^2
Velocity	Abstract	47 ± 6.7cm/s^2	45 ± 8.3cm/s^2
Velocity	Textured	69 ± 4.3cm/s^2	35 ± 6.3cm/s^2

$P = 0.0091$). While the texture made no difference to participant tolerance for acceleration errors ($t(17) = 0.22$, $P = 0.82$), it may have increased participant consistency with respect to those errors, as the JND was substantially lower ($t(17) = 2.33$, $P = 0.033$).

8. DISCUSSION

Our most directly applicable finding is that the visible gap between colliding objects appears to be an accurate predictor of user tolerance to gap errors for viewing angles up to about 40°. We note, however, that there appear to be multiple mechanisms by which participants are able to detect the presence of gap errors. Direct observation of gaps appears to dominate for low viewing angles, as participants converged to a mean PSE of about 6mm (0.4°) of visible gap regardless of viewing angle. At steeper viewing angles, and in particular at the 80° viewing angle where no gap was ever visible between the snooker balls, participants appear to have used a different technique to detect collision gap errors.

We were surprised to find that audio cues had no significant effect for any of the types of error, in contrast to findings that audio and visual cues can reinforce each other in tasks such as motion detection [Alais and Burr 2004]. Indeed, we note that for the purely audio error condition ("sound delay"), only 8 of 16 participants mentioned sound in their poststudy questionnaire, and responses were strongly bimodal, with 6 of 16 participants displaying strong convergence (all PSEs under 150ms, mean 59ms) and the other 10 participants displaying weak or no convergence (all PSEs over 400ms or not computable, as compared to a maximum error value of 500ms). One possibility is that most participants considered visual information to be of overriding importance, and largely dismissed audio cues, despite our explicit instruction to consider all information from the simulation. Indeed, in post-study questioning, one participant expressed surprise that the "sound delay" error condition (i.e., where the animation is correct but the sound is delayed) even existed.

Similarly, neither texture we tried had a significant effect on participant tolerance for angular or spatiotemporal errors, and there was no significant difference in participant tolerance for gap errors between any of the three scenarios we tested.

By contrast, we found a significant effect of scenario realism on participant response to angular distortions. Participants' tolerance for angular distortions did not differ significantly between the two nonsnooker scenarios we examined, and tolerance in those environments was very similar to that reported by O'Sullivan et al. [2003]; tolerance in the realistic snooker environment, however, was substantially higher. At least for the small set of scenarios we examined, abstract or neutral scenarios appeared to offer a conservative estimate of tolerance; however, it is possible that some scenarios will bias participants to be less tolerant of certain errors.

Indeed, while participant tolerance for errors was higher in the realistic snooker environment, participant sensitivity to angular distortions was also higher. While this result appears self-contradictory, it agrees with the findings of Hodgins et al. [1998] and Reitsma et al. [2008] who found that participants were better able to detect alterations to human animations on more detailed and realistic models. Accordingly, this combination of higher tolerance together with higher sensitivity should be expected, and further analysis may reveal common underlying causes.

Our data reveals that the root cause for both of these differences appears to be a response bias when reasoning about angular distortion errors; participants were systematically more likely to report a trial in a less-realistic scenario as containing an error, regardless of whether any error was actually present. Indeed, the most realistic-looking scenario (the basic snooker setup) received the lowest false alarm rate (3.6%) and the least realistic scenario (textured balls in the neutral scenario) received the highest (16.7%). One possible explanation is that unrealistic scenarios increase the amount of randomness and noise in user responses; this would account for the lower sensitivity for the unrealistic environment seen in Table V. Additionally, mean hit rates for the neutral environment were higher than the snooker environment (57.8% vs. 49.5%, respectively). Accordingly, another potential explanation is that participants were biased by the scenario and had a greater tendency to view motions in realistic scenarios as being realistic, and conversely motions in unrealistic scenarios as being unrealistic. We note that this response bias appeared to cut across participant level of experience with physics or snooker. The exception is that participants reporting snooker experience displayed equal sensitivity to angular distortions in both the snooker and nonsnooker environments, whereas participants with no such experience displayed substantially higher sensitivity in the realistic snooker environment; however, both groups displayed higher tolerance for errors in the realistic environment.

We note that all "global" errors (i.e., angular distortion and added acceleration, whose effects tend to be detected by inference from the overall motion of the balls) were significantly affected by the choice of scenario, while no "local" errors (i.e., spatiotemporal errors and velocity spikes, whose effects tend to be directly observed) were affected by the choice of scenario, with the exception of the effect of a high-contrast texture on participant tolerance of velocity spikes. However, this texture provides additional directly observable information, as the speed of dots on the surface of the ball provides additional observable cues to velocity changes. Indeed, the effect of a short-term change in velocity is likely to be magnified on the texture elements, as their apparent speed will be affected by increases to both the linear and rotational speeds of the ball. Accordingly, our results appear to indicate that participant tolerance for directly observable errors will tend to be unaffected by details of the scenario that do not directly impact on the observation of those errors, whereas participant tolerance for errors that are indirectly detected will tend to be much more sensitive to the choice of scenario. We caution that this is a preliminary finding, and in particular, we have only examined a subset of potential errors and static changes to the appearance of a scenario. Indeed, it is likely that dynamic scenario changes (e.g., the addition of distractors) will behave differently, as errors that are localized spatially or temporally may well be easier to miss due to momentary distractions.

9. CONCLUSIONS

In this article we find that the choice of scenario can strongly influence people's decisions on some types of errors. Tolerance to many commonly measured errors appears to be consistent between a neutral environment and the type of abstract setup use for some psychophysical studies. We note, however, that choice of scenario can systematically bias the decisions of users regarding certain types of errors and that different measures of how users are affected by errors may change in different ways due to such biases. Examining both tolerance and sensitivity to errors can help to uncover biases such as these.

We find that neither audio corresponding to the collision event nor the addition of a texture that provided information on object rotation had a significant effect on participant tolerance of angular distortion or spatiotemporal errors, although the texture did have a significant effect on participant tolerance of velocity spikes, as it provided additional information on those errors. We note, however, that in our experiments, an unrealistic texture appeared to bias participants to respond more negatively to motions, as did an unrealistic environment. More research is needed to determine how pervasive this type of bias may be.

Our results showed that participant tolerance of "local" or temporally localized, directly observable errors was unaffected by changes in scenario appearance that did not have direct bearing on the error, whereas tolerance of "global" or inferentially detected errors was much more sensitive to unrelated changes in scenario appearance. Additional research is needed to determine how generally this trend holds, particularly for other types of objects and for nonstatic changes to the scenario appearance.

Finally, we find that visible distance can accurately predict participant sensitivity to gap errors up to angles of 40°, potentially allowing greater flexibility in tasks such as approximate collision detection.

These findings provide guidance in applications where the figure of merit is perceived realism or plausibility rather than physical realism. For example, perceived gap can be used to approximate collisions and reduce computational requirements for animated systems (e.g., O'Sullivan and Dingliana [2001]), while information on angular distortion can be used to manipulate collisions within the bounds of plausibility and create animations that fulfill artist goals (e.g., Twigg and James [2007]).

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