The Sensitivity of Presence to Collision Response

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Abstract

This paper describes a new approach to collision detection and response, and an experiment to examine the sensitivity of subjective presence to varying collision response parameters. In particular, a bowling game scenario was used with 18 subjects, and parameters representing elasticity, friction and accuracy of collision detection were varied. Presence was assessed through a questionnaire following the experiment. The results suggested that presence was sensitive to variation in these parameters, and in particular to the value of the parameter representing friction.

Keywords

Presence, tele-presence, collision detection, collision response, virtual environments, virtual reality.

1. Introduction

In this paper we introduce a new method for handling collisions between objects in virtual environments (VEs). The impetus for this work arose out of our first pilot experiment in virtual reality in 1992 [SLAT 92], where here was an attempt to elicit factors that contribute to the subjective experience of 'presence' in an immersive VE - the sense of being in the environment depicted by the computer generated displays. The failure of the virtual world to exhibit expected physical laws (such as collision response) was reported as a factor that reduced the sense of presence. Since that first experiment our research program has been driven by an attempt to construct an empirically based model for the factors that influence presence - in particular, subjecting each technical development to a case-control experimental study to assess its potential influence on presence. For example, we have carried out such experiments in relation to the influence of a 'virtual body', with the 'virtual treadmill' walking technique [SLAT 95b], with the influence of dynamic shadows [SLAT 95a], and the influence of degrees of immersion on presence and task performance [SLAT 96]. In this paper we report an experiment to assess the sensitivity of presence to the collision detection and response methods described.

We have found it useful to distinguish between 'immersion' and 'presence'. Immersion is a term that we use to describe the extent to which the technology provides a capability for generating virtual worlds that are:

- *surrounding (S)* : sensory data may come from any direction to the participant's ego-centre;
- *extensive (E)*: supports multiple sensory modalities;
- *inclusive (I)* : where the real world is shut out;
- *vivid (V)*: with high resolution, richness and realism of the information portrayed by the displays;
- *matching (M)*: where the displays depict views of the virtual world that match in content and time the proprioceptive feedback about the movements and disposition of the participant's body. This should also include displayed information about the participant's virtual body.

Previously we have characterised 'subjective presence' along three orthogonal dimensions: the extent to which a *participant has a sense of*:

1. *being there (T)* - in the environment presented by the displays;
2. *reality* (R) - where the information presented by the displays is taken as more the current reality than the reality of the 'outside world';
3. *place (P)* - where the environment depicted by the displays becomes a 'place', recalled as a place on the same level as other real places that the participant has visited.

Our hypothesis is that presence, considered as an amalgam p(T,R,P) is an increasing function of the degree of match between proprioception and sensory data (M), and the degree to which the displays provide a surrounding, extensive, inclusive and vivid virtual world, which filtered through the participant's sensory preferences - allows them to build an internal and consistent world model. This model is a particular distillation of current thinking on presence; the most recent debate can be found in [SHER 96; ELLI 96].

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In this paper we focus primarily on ‘vividness’ [STEUR 92] in particular the degree of realism of the dynamic physical relationships between objects in collision. In the next section we outline the physical model, and later an experimental evaluation with respect to subjective presence.

2. Collision Detection and Response

When several objects are moving in a virtual environment, there is a chance that these objects will collide with each other. Typically, collision detection is a geometric intersection problem that depends on the spatial relationships between objects, while collision response is a dynamics problem which involves predicting behaviour according to physical laws. This section outlines a new collision detection method and a new collision response method developed for virtual reality applications.

2.1 Collision Detection

In a dynamic simulation environment such as virtual reality where the application context requires the appearance of correct operation of physical laws rather than their exact simulation, the prime consideration is to calculate the collision status of objects in real time with accuracy as a secondary consideration.

[MOOR 88] and [LAFL 91] use a polygon-vertex collision detection method for flexible surfaces. This method tests the penetration of each vertex of one polygon through the plane of the other, and simply testing vertices versus polygons in this manner is effective in many cases. A polyhedron-polyhedron collision detection method is also widely employed. This method can detect collisions only for convex polyhedra; however it is presumed that with some preprocessing a concave polyhedron can be decomposed into a collection of convex ones before applying this algorithm. The most basic algorithm of this class is to check each face of each polyhedron against the faces of other polyhedra and vice versa. This algorithm is very expensive computationally. When the numbers of polygons in each object are n and m, computation time is proportional to $m \times n$. Therefore, a variety of techniques such as bounding boxes and bounding spheres are used to increase speed [BARA 90; GANT 93]. Methods for parametric surface collision are given in [HERZ 90; SCLA 91] where the surface is expressed by functions which are continuous and twice differentiable with respect to time. If the surface functions of two objects have the same root, a collision has occurred. [SNYD 93] use time-dependent parametric and implicit surfaces to find collision points. This method detects simultaneous collisions at multiple contact points using an interval approach constrained minimisation. [BARA 89, 90] uses a characteristic function defining a distance between two objects near the contact point. This method uses a concept of ‘extreme distance’ between two objects. [LIN 91] proposes a method to calculate the smallest distance between two objects. Every polyhedron has three geometrical features, a vertex, an edge and a face. This method calculates the closest points between two objects by finding a pair of features which makes a distance minimum.

Since almost all of the collision detection methods mentioned above have to perform a collision detection test for every polygon or object surface, the collision condition cannot be decided until the last pair's test is finished. An efficient implementation might therefore employ a hierarchical method, including a rough check and an accurate check, to minimise the computational costs. However, since most objects in a virtual environment are separated from each other, an algorithm which detects *non*-colliding conditions could be used. A collision test can then be stopped when it is shown that a collision has *not* occurred. The *non*-colliding method for collision detection is used in the present work, which aims at providing a quick method for determining whether two convex objects do not collide. This same approach has been exploited by Chung and Wong [CHUN 96].

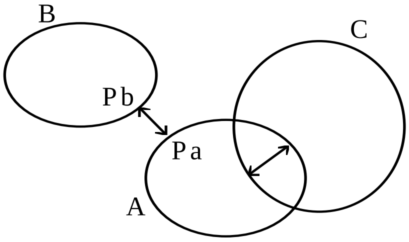

Figure 1
Relation Between Objects

Figure 1 shows the relationship between three convex objects A, B and C. Concentrating for the moment on A and B, P_a and P_b are points on the surfaces of object A and object B respectively, and N_a and N_b are normal vectors to the surfaces at points at P_a and P_b respectively where P_a and P_b are defined as follows: When the objects are separated, P_a is the closest point on the surface of object A to object B and similarly P_b is the closest point on the surface of object B to object A. When the objects are intersected, P_a is the point on the surface of object A which is furthest from the surface of B within the area of intersection, and P_b is the point on the surface of object B which is furthest from the surface object A within the area of intersection, in other words these define the points of maximal separation within the area of intersection. An example of this can be seen in the relationship between objects A and C. Hereafter, these points will be referred to simply as the *closest points.*

If P_a and P_b are the closest points on the surfaces between two objects, surface normal vectors N_a and N_b lie along the line passing through P_a and P_b and have opposite directions. In the other words, if two normal vectors N_a and N_b are the same vector but with opposite direction, points P_a and P_b corresponding to the surface points associated with the normal vectors are the closest points between two objects.

The collision status between two objects can thus be determined simply by inspecting P_a P_b, N_a and N_b. If a vector $D = P_b - P_a$ has the same direction as the vector N_a, the two objects are separated. On the other hand, if vector D has the opposite direction to the vector N_a, the objects are intersected. Additionally, the collision position P and the collision direction N (which are required to compute a collision response) as well as the distance between objects d can be expressed as:

$$P = (Pa + Pb)/2 \qquad (1)$$

$$N = (Na - Nb)/2 \qquad (2)$$

$$d = |D| = | Pb - Pa |$$

If the normal vectors N_a and N_b are determined, the collision position and the collision direction can be calculated. Therefore, the problem of the non-collision detection algorithm is to determine the normal vectors.

The normal vectors are calculated iteratively. At first, the normal vectors N_a and N_b are defined as vectors directed between centres of two objects (with $N_b = - N_a$). Then, positions P_a and P_b corresponding to these initial vectors are calculated as P_a and P_b being the furthest surface positions from the centre of each object in the direction of the corresponding vector. If a difference vector D, the vector between the positions, $(P_b - P_a)$, is parallel to N_a, the iteration terminates because the positions are the closest points. Otherwise, new estimates of the normal vectors are generated and new corresponding positions are determined. This iterative process is continued until the positions become the closest points, which is explained in full in [UNO 96].

If at any step of iteration the scalar product $N_a.D$ has a positive value, the two objects are separated, because parallel planes exist between them, and so the iteration can be terminated immediately if this is true.

After determining the closest points, the intersection of the two objects is determined by a sign of $N_a.D$. If the sign is positive, the objects are separated. If the sign is negative, they are intersected. If the objects are intersected, the collision position and the collision direction can be derived by using equations (1) and (2).

This method can be applied both for an object defined as a parametric surface and for an object defined with geometrical vertex data. Composite objects composed of primitive parametric functions such as ellipsoids, cylinders, and cones are also handled by this method. In the experiments carried out in this research, all objects were such composite parametric surfaces.

Although it is not the main point of this paper, it is worth mentioning that current results show that this method performs well in comparison with the polyhedron-polyhedron collision detection method [BARA 90; GANT 93] which tested each point and edge of one object as to whether it was inside the other object. In simulation studies to date, two geometry data sets have been used for the evaluation, one comprising 7 compound objects, composed of a total of 22 polyhedral primitives with 419 polygons, and the other comprising 7 compound objects, composed of a total of 22 polyhedral primitives with 970 polygons. These data sets thus have same number of objects, but differing numbers of polygons. The results indicated that the non-collision detection method is between 2.5 and 8 times faster than the polyhedron-polyhedron method for these data sets. Further, the calculation time of the non-collision detection method increases in proportion to the number of polygons, whereas, the time of the earlier method increases geometrically. In addition, a collision position and a collision direction are trivially derived from the closest points in the non-collision detection method, while in the earlier method this is not the case.

2.2 Collision Response

Collisions in dynamic simulations are usually resolved by analytical methods. The conservative laws of linear and angular momentum are used for this purpose [MOOR 88; HAHN 88; MIRT 95] and the result depends on the collision behaviour, i.e. on parameters such as elasticity and friction.

Analytical methods attempt to solve a collision response correctly using physical laws, and special cases such as a complete inelastic collision and elastic collision without friction can be calculated correctly. However, some cases, for example the case of an elastic, rolling collision, cannot be determined correctly because the conservative law of kinetic energy is not taken into account. If a collision has occurred between two elastic objects which have completely rough surfaces, the objects roll over each other at a collision point, and as a result kinetic energy is conserved. The conservative law of kinetic energy is considered in this paper.

(a) Physical Equations

To solve a collision, three kinds of equation are typically used: the conservative laws of momentum, the conservative law of kinetic energy, and the relative velocity at the collision position after collision.

In this paper, m_a and m_b are masses of the objects A and B respectively, $\mathbf{I_a}$ and $\mathbf{I_b}$ are their inertial momentum matrices, $\mathbf{S_a}$ and $\mathbf{S_b}$ are rotation matrices, V_a and V_b are the velocities before collision, and W_a and W_b are angular velocities before collision. If the objects are compound objects, physical parameters refer to the whole objects.

The new velocities V_a', V_b' and the new angular velocities W_a', W_b' are expressed by the conservative laws of momentum as follows, where the equations (5) and (6) are in the object coordinates, R_a and R_b are collision positions in the local coordinates of object A and object B, and F is the impulse at the collision point. Two impulses on object A and object B have the same magnitude and opposite directions because of

Newton's third law of motion. F_a and F_b are impulses in the local coordinates of each object.

$$m_a V_a' - m_a V_a = F \quad (3)$$
$$m_b V_b' - m_b V_b = -F \quad (4)$$
$$W_a'\mathbf{I_a} - W_a \mathbf{I_a} = R_a \times F_a \quad (5)$$
$$W_b'\mathbf{I_b} - W_b \mathbf{I_b} = R_b \times F_b \quad (6)$$

Equations (3)-(6) show that the new velocities and the new angular velocities are expressed by the impulse F. Therefore, if F is determined, all unknown parameters V_a',V_b',W_a' and W_b' can be calculated.

To determine the impulse F, the conservative law of kinetic energy and relative velocity at the collision position after collision are used. The following equation shows the conservative law of kinetic energy applied to two collided objects. The left hand side is (twice) the kinetic energy after collision and the right hand side is (twice) the kinetic energy before collision.

$$m_a V_a'.V_a' + m_b V_b'.V_b' + W_a' \mathbf{I_a}.W_a' + W_b' \mathbf{I_b}.W_b'$$
$$= m_a V_a.V_a + m_b V_b.V_b + W_a \mathbf{I_a}.W_a + W_b \mathbf{I_b}.W_b \quad (7)$$

Relative velocity dV at the collision position after collision is also used to determine the impulse F. dV is expressed as a difference of linear velocities, V_a' and V_b', and a difference of rotation velocities, $W_a' \times R_a$ and $W_b' \times R_b$, as follows.

$$dV = V_a' - V_b' + (W_a' \times R_a)\mathbf{S_a} - (W_b' \times R_b)\mathbf{S_b} \quad (8)$$

(b) Energy Conservation Method

The method to solve a collision is now described. Physical parameters, elasticity ε and friction μ, are considered to determine an impulse F. These parameters are employed in previous methods to calculate a realistic collision. The method described here simplifies the handling of elasticity and friction to give the illusion of their correct operation, but without the computational expense of full simulation.

In this method elasticity and friction values are defined for every object as coefficients between 0 and 1. Then an actual coefficient between two collided objects is determined by multiplying the two corresponding coefficients of the objects. If the product of the two friction values μ ($0 \le \mu \le 1$) is 0, the two objects slide over each other at the collision position, and impulse F corresponds to the collision direction. If μ is 1, the two objects roll over each other at the collision position, and the components of the velocities of the two objects in the collision tangent plane are equal at the moment of collision. If the multiplied elasticity ε ($0 \le \varepsilon \le 1$) is 0, impulse F lies along the collision tangent plane, and the velocities of the two objects are equivalent in the collision direction after collision. If ε is 1, the two objects are considered as rigid bodies, and kinetic energy is conserved if an actual friction between objects is 0 or 1. (If the friction is not 0 nor 1, kinetic energy is not conserved even if the elasticity is 1). The friction described above is not as same as the usual friction coefficient of physics, and should be called *friction rate*; however, the term 'friction' is used in this paper.

To determine an impulse F, four impulses corresponding to the special collision conditions are first calculated.

(i) Impulse F_{10} in the case of $\varepsilon = 1$ and $\mu = 0$.
If elasticity is 1 and friction is 0, a collision has occurred between perfectly elastic and smooth surfaces. Since the surfaces are smooth, two collided objects slide over each other at the collision position and so the direction of impulse F_{10} corresponds to the collision direction N ($F_{10} = f$ N). Since N is known, the problem is to determine the magnitude of impulse f. Kinetic energy is conserved in this case and so the magnitude f can be determined using equation (7).

(ii) Impulse F_{11} in the case of $\varepsilon = 1$ and $\mu = 1$.
If elasticity is 1 and friction is 1, a collision has occurred between perfectly elastic and rough surfaces. Since the surfaces are rough, the two collided objects roll over each other at the collision position without sliding, and so the velocity components of the objects at the collision position in the collision tangent plane are equal at the moment of collision, and relative velocity dV corresponds to the collision direction N. This can be expressed as dV = k N, where k is a coefficient to be determined. Kinetic energy is again conserved and so the coefficient k can be determined using equation (7).

(iii) Impulse F_{00} in the case of $\varepsilon = 0$ and $\mu = 0$.
If elasticity is 0 and friction is 0, a collision has occurred between perfectly inelastic and smooth surfaces. Since the surfaces are smooth, the two collided objects slide over each other at the collision position, and so the direction of impulse F_{00} corresponds to the collision direction N ($F_{00} = f$ N). Since N is known, the problem is to determine the magnitude of impulse f. The fact that the collision is inelastic means that velocities of two objects at the collision position after collision are equivalent with the collision direction N, so relative velocity dV is on the collision tangent plane. This means dV and N are perpendicular, and so the dot product between dV and N is 0 (dV.N = 0). The magnitude f can be determined using above two equations and equation (8). (Kinetic energy is not conserved in this case).

(iv) Impulse F_{01} in the case of $\varepsilon = 0$ and $\mu = 1$.
If elasticity is 0 and friction is 1, a collision has occurred between perfectly inelastic and rough surfaces. Since the surfaces are rough, two collided objects roll over each other at the collision position without sliding, and so the velocities of two objects at the collision position after collision are equivalent in the collision tangent plane. In addition, since the collision is inelastic, the velocities of two objects at

the collision position after collision are equal in the collision direction N. This means the velocities of two objects at the collision position are exactly the same after collision, thus the relative velocity dV should be 0 (dV = 0). Kinetic energy is not conserved in this case, and the direction of impulse F_{01} does not correspond to the collision direction N because of friction between the objects. Impulse F01 can be determined easily by using equation (8).

After calculating the four impulses corresponding to the special conditions, an actual impulse $F_{\varepsilon\mu}$ in a general condition with an arbitrary elasticity (0 < ε < 1) and an arbitrary friction (0 < μ < 1) is determined. The impulse in a general case cannot be determined exactly by the method for the special cases using kinetic energy and relative velocity. However, from the point of view of the VR approximation, a result may be obtained by linear interpolation as follows:

$$F_{\varepsilon\mu} = F_{00}+(F_{10}-F_{00})\varepsilon+(F_{01}-F_{00})\mu+(F_{11}-F_{01}-F_{10}+F_{00})\varepsilon\mu \qquad (9)$$

After determining $F_{\varepsilon\mu}$, four unknown velocities V_a', V_b', W_a', W_b' after collision can be calculated using equations (3)-(6).

3. Experiment

An experiment was conducted to examine the influence of the parameters controlling elasticity, friction and shape. The formulation given in equations (1) - (9) was implemented, and the effect on subjective presence of varying these parameters investigated. The experimental scenario took the form of a game of pin bowling (see Plates). Each subject was required to play two bowling games, and there was a change in value of one of these parameters as between the two games. The subjects then completed a questionnaire which included six questions on presence constructed as variations on the three dimensions discussed in Section 2 providing data for the response variable for this experiment. The questionnaire also asked whether they noticed any difference between the two bowling sessions.

The implementation was on a DIVISION ProVision100, with a Virtual Research Flight Helmet and a DIVISION 3D Mouse. Polhemus Fastrak sensors were used for position tracking of the head and the mouse. The generated image has a resolution of 704x480 which is relayed to two colour LCDs each with a 360×240 resolution. The HMD provides a horizontal field of view of about 75 degrees, and about 40 degrees vertically. Forward movement in the VE is accomplished by pressing a left thumb button on the 3D mouse, and backward movement with a right thumb button. A virtual hand was slaved to the 3D mouse - there was no virtual body representation other than this. Objects could be touched by the hand and grabbed by using the trigger finger button on the 3D mouse.

The parameters controlling elasticity and friction can be between 0.0 and 1.0. A value of 0.7 for elasticity or friction results in a product of 0.49 (i.e., approximately 0.5). This was used in comparison to 0.0 for friction and 1.0 for elasticity. Objects could be represented as their actual shape or be approximated by ellipsoids. The trials prior to the experiment varied the maximum number of iterations for collision detection between 5 and 20. However, in these preliminary trials no subjects were ever able to distinguish the results of changes in the maximum number of iterations, so this was fixed at 20 throughout.

For the purposes of the experiment we treat each of elasticity (E), friction (F) and shape (S) as a binary variable, as shown in Table 1.

Table 1
Parameter Values used in the Experiment

Parameter	Binary Value: 0	Binary Value: 1
Elasticity	elasticity = 1.0	elasticity = 0.7
Friction	friction = 0.0	friction = 0.7
Shape	Ellipsoid	True shape

Table 2 shows the distribution of the 18 subjects in the main experiment into the cells of the factorial design. The first column indicates the binary parameter values. The ‘Changed Parameter’ column refers to the parameter that had its value changed for the corresponding subjects. For example, the two subjects allocated to the first row carried out one bowling game with all three parameter values at ‘0’ and the other game with elasticity and friction at ‘0’ and shape at ‘1’. The subjects were allocated randomly to the rows of the table.

The subjects were recruited by advertisement in the College, and consisted of 10 students, 3 research workers, 3 office staff, and 2 others. There were 12 male subjects out of the 18. None of the subjects were aware of the purpose of the experiment, nor had been in contact with the research before, although 7 answered ‘yes’ to the question ‘Have you experienced “virtual reality” before?’.

Table 2
Experimental Design

EFS	Changed Parameter	No. of Subjects
000	Shape	2
000	Friction	2
000	Elasticity	2
100	Shape	1
010	Shape	1
100	Friction	1
001	Friction	1
010	Elasticity	1

001	Elasticity	1
110	Shape	2
101	Friction	2
011	Elasticity	2
TOTAL		**18**

The questionnaire included a question relating to possible experience of simulator sickness *('How dizzy, sick or nauseous did you feel resulting from the experience, if at all?')*. This was rated on a 1 to 7 scale with 1 = 'not at all' and 7 = 'very much so'. The results are shown in Table 3.

Table 3
Reported Sickness Level

Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**
%	28	28	17	0	17	6	6	**18**

The subjective presence score was constructed from the six 1 to 7 scale questions shown in Appendix A, where '1' indicated low presence, and '7' high presence (the term 'presence' was of course *not* used at all in questionnaire). These six questions are variations on the theme of the three aspects of subjective presence that we have used in previous experiments, as outlined in Section 1. The subjective presence variable was, as previously, conservatively taken as the number of high ('6' or '7') answers over the six questions, and was therefore a count between 0 and 6.

4. Results

Table 4 shows the distribution of subjects according to whether or not they noticed the changes in values for each parameter. *('There were two versions of the game, accessed by pressing the Red or Blue buttons. Could you distinguish any differences between how things worked in these two versions of the game?')*. In the case when elasticity was the changing parameter value, half of the subjects noticed the change. In the case of friction, all subjects observed the change. In the case of the shape, no subjects observed the change.

The main analysis was carried out using logistic regression [COX 70] where the response variable p is the 'high score' count out of six as explained above. This is treated as a binomially distributed variable (where 'success' = 'high score'), and the expected value of this variable is related by a logistic function to a linear combination of the independent and explanatory variables (Appendix B).

Table 4
Response to Parameter Changes
Numbers of Subjects who perceived the changes:

	Elasticity	**Friction**	**Shape**
No change observed	3	0	6
Change observed	3	6	0
Total	**6**	**6**	**6**

Table 5
Summary of Logistic Regression Model

Parameter Changed	**Fitted Linear Predictor**
Elasticity	Const. - 0.7*sick + 2.1*F
Friction	Const. - 0.7*sick + 3.8*S - 3.8*E
Shape	Const. - 0.7*sick + 2.1*F

χ^2 = 12.727 d.f. = 8, Tabulated χ^2 = 13.362 for P = 0.10

Table 5 shows a summary for the best fit model. The overall goodness of fit is tested by a Chi-squared statistic, where a smaller value indicates a better fit. Here the overall Chi-squared value is between the 20% and 10% tail of the distribution. No variable can be removed from the model without significantly worsening the fit (at a 5% significance level). A significant explanatory factor (hidden in the constant term) included whether the subject had 'experienced VR before.' A 'yes' answer decreased the reported presence. Also the extent of reported sickness was negatively associated with reported presence under all conditions.

There is no difference in results when elasticity or shape are the changing parameters. Here it is the effect of whether or not friction is at the higher (0.7) value, which is positively associated with the presence count. When friction is the changing parameter presence is positively associated with correct shape (S = '1') and negatively associated with elasticity (i.e., an elasticity of 1.0 is associated with higher presence than elasticity of 0.7). Since the change in friction was the only parameter always noticed by the subjects, this supports the idea that it is this parameter which had the greatest impact amongst the three for this particular experimental simulation.

5. Conclusions

The aim of this paper has been to introduce a method for collision detection and response, and to examine the influence of the technique on reported presence. The most important result regarding presence is that there is a quantifiable and statistically significant influence at all. The collision response technique, although much simplified compared to a full simulation of these parameters nevertheless seems to give results acceptable in the circumstances of the bowling game. Subjects were invited to comment on the experiment immediately afterwards, and although there were comments on the weight of the HMD, the difficulty of object selection, the difficulty in finding the right moment to release the virtual ball after swinging the arm, there were no comments about the behaviours of the virtual objects in response to collision.

This was the first experiment where we have attempted to examine the influence of such physically based behaviour of objects in VEs. Future work will take a larger number of subjects and vary the three parameters (E, F, and S) over a wider range of values, rather than the binary choices used here. Moreover, this experiment has concentrated on the sensitivity of *subjective* presence. In the context of collision response there is opportunity to also examine *behavioural* presence; for example, in this experiment we noticed that subjects did attempt to get out of the way when objects (skittles or balls) came bouncing back towards them (one person exclaiming “This is dangerous!”). It will be possible in future work to take systematic observations of such events and include them in the analysis.

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Acknowledgements

This work is partially funded by Canon Inc., and the London Parallel Applications Centre as part of a grant from the UK DTI and EPSRC. There is partial funding from the EPSRC DEVRL project, grant number GR/K38090.

Appendix A: Presence Related Questions

1. Please rate *your sense of being there* in the room shown by the virtual reality on the following scale from 1 to 7.

2. To what extent were there times during the experience when the virtual reality games became "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?

3. When you think back about your experience, do you think of the virtual reality more as *images that you*

saw, or more as *somewhere that you visited* ? Please answer on the following 1 to 7 scale.

4. During the time of the experience, which was strongest on the whole, your sense of being in the virtual reality, or of being in the real world of the laboratory?

5. When you think about the virtual reality, to what extent is the way that you are thinking about this in a similar way that you are thinking about the various real places that you've been today?

6. During the course of the virtual reality experience, did you often think to yourself that you were actually just standing in a laboratory wearing a helmet, or did the virtual reality overwhelm you?

Appendix B: Logistic Regression

Let the independent and explanatory variables be denoted by $x_1, x_2, ..., x_k$. Then the linear predictor is an expression of the form:

$$\eta_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} \quad (i = 1,2,...,N) \tag{1}$$

where N (=18) is the number of observations. The logistic regression model links the expected value $E(p_i)$ to the linear predictor as:

$$E(p_i) = \frac{n}{1+\exp(-\eta_i)} \tag{2}$$

where n (=6) is the number of binomial trials per observation (the three presence questions). Maximum likelihood estimation is used to obtain estimates of the β coefficients. The deviance (minus twice the log-likelihood ratio of two models) may be used as a goodness of fit significance test, comparing the null model ($\beta_j = 0$, j = 1,...k) with any given model. The change in deviance for adding or deleting groups of variables may also be used to test for their significance. The (change in) deviance has an approximate χ^2 distribution with degrees of freedom dependent on the number of parameters (added or deleted).

Table 6
Parameter Estimates and Standard Errors
(Non-significant at 5% level shown in italics).

estimate	**S.E.**	**parameter**
1.501	1.216	change(1)
-0.9969	1.125	change(2)
0.7149	0.8994	change(3)
2.112	0.9312	F
-0.6980	0.2461	sick
-1.580	0.7133	vrbefore(2)
-1.496	*1.213*	*change(1).S*
3.786	1.440	change(2).S
-3.836	1.443	change(2).E
-0.5273	*1.116*	*change(3).E*

Table 6 shows the details of the model fitted in this case. The levels of the factors are shown in brackets in the last column. Change(1),(2),(3) refers to whether elasticity (1), friction (2) or shape (3) are the parameters being changed. vrbefore (2) is ‘no previous VR experience’. change(x).Y refers to the coefficient of Y when x is the parameter being changed. Impossible combinations are not shown.

Plates: Uno and Slater.