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A Virtual Presence Counter

Abstract

This paper describes a new measure for presence in immersive virtual environments (VEs) that is based on data that can be unobtrusively obtained during the course of a VE experience. At different times during an experience, a participant will occasionally switch between interpreting the totality of sensory inputs as forming the VE or the real world. The number of transitions from virtual to real is counted, and, using some simplifying assumptions, a probabilistic Markov chain model can be constructed to model these transitions. This model can be used to estimate the equilibrium probability of being "present" in the VE. This technique was applied in the context of an experiment to assess the relationship between presence and body movement in an immersive VE. The movement was that required by subjects to reach out and touch successive pieces on a three-dimensional chess board. The experiment included twenty subjects, ten of whom had to reach out to touch the chess pieces (the active group) and ten of whom only had to click a handheld mouse button (the control group). The results revealed a significant positive association in the active group between body movement and presence. The results lend support to interaction paradigms that are based on maximizing the match between sensory data and proprioception.

1 Introduction

Imagine that you are walking through a sunlit park, perhaps admiring the trees. A particular tree is interesting, and you begin to move closer to it. As you get within a certain distance, you suddenly realize that the tree is flat—a virtual cardboard cutout. You recall that you're actually in the laboratory, wearing a head-mounted display (HMD), and it is the middle of the night. After a short time, you carry on walking through the park, looking for the exit. At one moment, you turn your head quite fast, and notice that the image lags behind your head movement. Once again, you are back in the laboratory, aware of the HMD and of the cables wrapped around your legs. Later, having found the way out of the park, you are watching the traffic and waiting for a chance to cross the road. Just as you start to move across the road, you hear a voice shout, "You still here at this time of night?" Once again, you're back in the laboratory, recalled to reality by the building superintendent.

This paper offers an approach to the elicitation of presence in a virtual environment (VE), based on such transitions from the virtual to the real. The goal is a measurement technique that reduces reliance on questionnaires and that gathers information during a VE experience rather than only when it is over. The measure is applied in an experiment that is designed to explore the relationship between body movement and presence. The results indicate a positive

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association between these two, which is important for the design of interaction paradigms for immersive VEs. This study reproduces the findings of another recent experiment on the relation between body movement and presence (Slater et al., 1998) but which used traditional questionnaire-based methods.

Because the approach to the elicitation of presence introduced in this paper is quite different to anything tried before, it is worthwhile to briefly discuss the overall methodology. Based on a set of simplifying assumptions, a stochastic process is developed in an attempt to model the number of transitions experienced by VE participants between the two states: "presence in the VE" and "presence in the real world." Based on the stochastic model, an estimator for the proportion of time spent in the "presence in the VE" state is constructed. Of course, there is no suggestion that the assumptions or the model that flows from it are "true" as a description of real-world mental or behavioral processes; rather, they provide an abstraction against which data can be collected.

2 Background

In this section, we consider the background on two interrelated questions: the definition of presence and its elicitation and measurement. An extensive review can be found in Draper, Kaber, and Usher (1998) who identify three types of presence in the literature: simple, cybernetic, and experiential. The first is simply the ability to operate in the virtual environment, and the second is concerned with aspects of the human-computer interface. In this paper, we concentrate on the third of Draper et al.'s types—the experiential approach, in which presence "is a mental state in which a user feels physically present within the computer-mediated environment." This follows the common view that presence is the sense of "being there" in the virtual environment, or, equivalently, presence in a virtual environment involves the sense of being in the virtual place rather than in the real physical place (such as the laboratory) where the person's body is actually located (Held & Durlach, 1992; Sheridan, 1992; Barfield & Weghorst, 1993; Slater, Usoh, & Steed, 1994; Sheridan, 1996; Ellis, 1996; Witmer & Singer, 1998).

A quite different approach (Zahoric & Jenison, 1998) gives a working definition of presence as "tantamount to successfully supported action in the environment." This approach emphasizes that reality is grounded in action rather than in mental filters and sensations and that "the reality of experience is defined relative to functionality, rather than to appearances" (Flach & Holden, 1998). This approach concentrates on action (how participants do things) rather than how things look and sound, and that *being there* is actually the ability to *do* there. The VE becomes endowed with "there-ness" through this process of action and interaction. The present paper supports this view, and, indeed, the experiment does support the idea that action in the sense of appropriate whole-body movements is associated with a higher sense of presence. It will be argued that one group of our subjects had the chance to learn their environment through body movements rather than through just seeing it, and that these subjects reported a greater sense of presence. Nevertheless, we do see value in a construct such as presence—the sense of being there—that is independent of the "action" in which it is embedded.

Some authors have distinguished between immersion and presence. In this view, *immersion* is a term used for describing the technology that can give rise to presence. For example, Draper, Kaber, and Usher (1998) write that "immersion is the degree to which sensory input to all modalities is controlled by the SE {synthetic environment} interface." A fundamental research goal is to understand how presence is influenced by these (immersive) properties of the system that generates the VE, and by the rules and methods by which people interact within it (Slater & Wilbur, 1997). Ellis (1996) has argued that the equation relating presence to its influencing factors must be such that iso-presence curves can be constructed, thus allowing an understanding of how different configurations and combinations of these factors can be used to attain a given level of presence. This is an important engineering requirement, allowing tradeoffs between various system components, for example, for economic considerations. Bystrom, Barfield, and Hendrix (1999) have recently produced a framework for presence research that also embodies this distinction between immersion and presence.

Despite the widespread agreement on the concept of presence, its measurement has many different approaches. Some studies avoid the issue of measuring presence by examining the impact of more (or less) presence on success in the performance of a task within a VE. For example, Pausch, Proffit, and Williams (1997) used this approach in the context of a search task. Presence was not measured but was assumed to follow from a more immersive setup (use of a head-tracked, head-mounted display). However, what this study really showed was the impact of different levels of what we have called *immersion* on the task performance, rather than presence—for a simple relationship between immersion and presence cannot be assumed. The need to measure presence independently of immersion is necessary also because immersion might influence presence and task performance in different ways.

The qualitative or ethnographic approach to presence involves in-depth studies with relatively few people, or with case histories, in order to gain substantial insight into the phenomenon and its relationship to other factors. This approach is exemplified, for example, by the work of McGreevy (1993) and Gilkey and Weisenberger (1995). Both examined the notion of presence among people in relatively extreme circumstances: the first of geologists in the field on a Mars-like terrain and under varying arrangements of their visual field of view, and the second of the suddenly deafened adult. Profound insights into the nature of presence (or its absence) can be elicited in this way.

Another approach is to attempt to measure presence by observing people's behavior. Held and Durlach (1992) suggested a "startle" or looming response. This was extended by Sheridan (1992) to "socially conditioned" responses (would a person involuntarily put out their hand in response to a hand-shake gesture?). In Slater, Usoh, and Chrysanthou (1995) an attempt was made to measure presence behaviorally by introducing contradictory information about an object represented in both the real and virtual world, with some information (visual) coming from the VE and other information (auditory) from the real world. The extent to which participants respond to the visual information (allowing for differences in sensory preference) indicates their degree of presence in the virtual. A similar approach, although in the vestibular domain, has been tried by Prothero et al. (1995).

These behavioral techniques all suffer from the same problem: some feature or task has to be added to the environment (to cause the looming response, for example) that may have nothing to do with the application, but is only there for the purpose of measuring presence. A good property of a measuring instrument should be the extent to which it can be used in any application without the addition of particular features that are for the sole purpose of measurement.

A variation on the behavioral approach was suggested by Barfield and Weghorst (1993) and by Welch (1997). Both studies suggest that presence in the VE would induce aftereffects in participants once they had left the VE. The intensity and extent of such aftereffects could be used as a measure of presence. As Welch points out, though, the relationship is a complex one. He argues that the intensity of such aftereffects will have a negative correlation with the degree of initial presence, and a positive correlation with longer-term adaptive presence. Although measurement techniques could be constructed on this basis, none have appeared in the literature to date.

By far the most common approach to the elicitation of the degree of presence is through subjective reporting, usually in conjunction with a questionnaire. Barfield and Weghorst (1993) measured presence using subjective reporting on ten-point scales with three questions that proved to be highly correlated: the sense of being there, the sense of inclusion in the virtual world, and the sense of presence in the virtual world. Slater, Steed, and Usoh (1993) required subjects to rate their sense of "being there" in the virtual environment, the extent to which the VE became their dominant reality, and the extent to which the VE became a place, rather than just images. Each of these was rated on a scale of 1 to 7, and the presence score was taken as the number of high scores (6 or 7). This questionnaire has been extended in several further studies, adding more questions, each based on one of the three main ideas, most recently in Usoh et al. (1999).

Welch et al. (1996) used the method of paired comparisons. *Presence* was defined to the subjects, and they were required to choose a value between 1 and 100 to indicate the "size of perceived difference" between the presence-impact of two environments. Their definition of *presence* "emphasized the feeling that subjects were physically located in and surrounded by the portrayed visual world, rather than in the laboratory in which they knew the experiment to be taking place."

Hendrix and Barfield (1996a) used a questionnaire with an anchored 1-to-100 scale around three aspects of presence: one question involved use of the term *presence* itself, the second the sense of being there in the virtual world, and the third the level of realism of the virtual world. Subjects were instructed to answer 100 for a sense of presence equivalent to the real world, and 1 for no presence. The same approach was used in their later study (Hendrix & Barfield, 1996b).

Witmer and Singer (1998) define *presence* as "the subjective experience of being in one place or environment, even when one is physically situated in another" and "presence refers to experiencing the computer-generated environment rather than the actual physical locale." They construct a questionnaire based on 32 influencing factors, each rated on a scale of 1 to 7, such as control factors ("How much were you able to control events?"), sensory factors ("How much did the visual aspects of the environment involve you?"), distraction factors ("How aware were you of events occurring in the real world around you?"), and realism factors ("How inconsistent or disconnected was the information coming from your various senses?"). Their presence measure is then the sum of responses to the 32 questions, and they also try to identify important determinants by examining correlations between the individual factors and the overall sum. This approach is interesting, because, unlike the earlier-mentioned approaches, their measure does not directly attempt to elicit presence according to their definition of the word. Instead, the measure is based on subjective responses to various aspects of immersion (in the sense described earlier in this paper, as properties of the VE delivering system itself). A critique of Witmer and Singer's approach may be found in Slater (1999) followed by their reply.

One problem with the use of subjective rating scales is that the scores are ordinal, and therefore strictly should not be combined together to form summations. The Slater, Steed, and Usoh (1993) approach avoids this problem by taking the overall score as a count of high responses out of the number of presence questions. Under the null hypothesis that responses are statistically independent, the overall count has a binomial distribution, and, therefore, logistic regression may be used in analysis. Snow and Williges (1998) obtain a ratio-scale measurement of presence by using free modulus magnitude estimation. Each subject provides a number (degree of presence) in response to a stimuli and is free to give a different number in response to different stimuli. Snow and Williges show how to combine these numbers to obtain a ratio-scale that is valid within and between subjects. They seem to side-step the issue of defining presence, and report that subjects "were asked to assign a number to their feeling of how much they felt as if they were actually present in the virtual environment during performance of the tasks in that trial."

Still using the same idea of subjective reporting, Freeman et al. (1999) adapt methods of continuous assessment of TV-picture quality to assessing presence. While viewing a VE, subjects are able to manipulate a handheld slider indicating their sense of presence, "defined for observers as 'a sense of being there' in a displayed scene or environment." The experiments involved changing various aspects of the presentation (such as from monoscopic to stereo), and, indeed, corresponding changes in the recorded presence scores were found.

A difficulty with this procedure is that there is no control. When observers see some change in the display quality, the only response available to them in the context of the experiment is either to do nothing or to move the slider. As a control, it would be interesting to repeat the series of experiments described, but calling the slider a measure of "factor X" and examining whether the pattern of responses is similar to those of presence.

Freeman et al. also show how subjective assessment can be influenced by the prior training and experimental conditions. Although this is a general problem in presence research, it is exacerbated by the tendency to use within-group experimental designs, in which subjects experience a number of different stimuli and are asked to rate the presence level corresponding to each (whether during or after the trial). When studies on humans involve responses that are involuntary (for example, pupil dilation in response to brightness), it is reasonable and normal to use within-group designs. However, in the case of presence, where the response is subjective and voluntary, subjects can clearly be influenced in their responses by the information that they gather during the course of the experiment. For example, if they experience two VEs, one with full color and the other only monochrome, they can quickly figure out that the experimenter (other things being equal) would be expecting a higher sense of presence in the full-color one. In the context of the slider, this problem is taken to an extreme, because subjects experience within the same session different aspects of the quality of the display, so that it must become very obvious what the point of the experiment is, and what the expectations associated with it are. Freeman et al. are, for this reason, aiming to move towards more-objective methodologies.

From the discussion above, it would be easy to conclude that presence is a relationship of an individual to an environment, and that the degree of presence is quantifiable and may vary more or less continuously. We consider these assumptions in more detail. Imagine an individual receiving and aware of sensory stimuli from only one environment.[1] In our approach to presence, the individual would, by definition, be present in that environment. The issue of presence becomes interesting only when there are competing environments—that is, the individual is receiving and can be aware of stimuli from multiple environments (including internal ones). Presence then determines which of the environments the individual responds to and acts within at any given moment. Slater, Usoh, and Steed (1994) defined the displayed environment (E_D) as that created by the VE system. Then, given any environment E, the notation $p(E|E_D)$ was used to represent the degree of presence in E, given that the individual was "in" E_D. Presence in the VE was then defined as $p(E_D|E_D)$.

1. Here we include internal stimuli as constituents of valid internal mental environments, so the worlds of daydreaming would be included as an environment.

A rigorous analysis by Schloerb (1995) operationalized this by treating the degree of presence explicitly as a probability measure: "the degree of subjective presence is defined to be the probability that the person perceives that he or she is physically present in the given environment." Schloerb describes a thought experiment in which an individual randomly receives stimuli from the physical environment or from a similar virtual environment, and each time is asked to state which of the two environments (physical or virtual) he or she is in. This allows a probability estimation of the degree of presence.

As Draper, Kaber, and Usher (1998) have pointed out, Schloerb's approach treats subjective presence as binary where experience is "bifurcated into *telepresent* and *not-telepresent* experiences, whereas other authors consider telepresence continuously scalable."

If we return to the idea of presence as the potential to act in an environment, then all this can be tied together. Suppose the individual is receiving stimuli from a number of competing environments (the physical world in which the person is standing, the virtual world, and internal mental worlds such as memories and daydreams). At any moment, the person responds and acts with respect to one of these environments. By this, we mean both the shifting of attentional resources towards the specific signals belonging to that environment, as well as the response to those signals: direction of gaze, attention to particular sounds, awareness of parts of the body such as the pressure on the soles of the feet caused by standing on the floor, awareness of a sudden draft, and voluntary actions such as body movements and utterances. Returning to the opening example of this paper, at one moment the individual is aware of and responding to the stimuli from the virtual park and is not paying attention to the vast array of other signals that constitute the physical environment of the laboratory and its surroundings. When presence in the park is broken, for example, by a glitch in the display or a sudden noise from the real world, at that moment the individual is hardly aware of the virtual park stimuli and much more aware of the temperature in the laboratory, the weight of the HMD, sensations such as pressures and contact with other objects on his or her physical body, and so on. We can think of presence as a selector among environments to which to respond, which operates dynamically from moment to moment. If it were possible to freeze time at a specific instant, the individual would be paying attention and responding to a set of stimuli that corresponds to one environment and ignoring stimuli from other environments. Also they may be interpreting stimuli from one environment in the context of the currently present one (for example, interpreting a sound from the real world as belonging to the virtual world). A fundamental proposal of this paper is that the set of stimuli of the *present environment* forms an overall gestalt, providing a consistent believable world in itself. This overall idea of considering attentional resources as part of the determination of presence is also included in the Immersion, Presence, and Performance framework of Bystrom, Barfield, and Hendrix (1999).

Now the view of presence as the selection of one among multiple environments at any moment in time is certainly not inconsistent with continuous measures. For example, at any moment in an experience, the individual can be asked to rate the degree of presence in the VE, and the response is determined by an integration over the last small interval of time. Or, at the end of an experiment, a questionnaire rating may be determined by, for example, an integration over the whole time period. Schloerb's thought experiment of asking the individual to choose between presence in the VE and presence in the real world is also compatible with this: the individual would say "yes" to presence in the VE if at that moment she or he was about to respond to the VE stimuli rather than the real-world physical or other stimuli.

The main contribution of this paper is an attempt to introduce a measure that is this integration over time. It is based on the idea of a gestalt formed from stimuli at any moment in time, and the construction of a very simple stochastic model for this. Within the context of the stochastic model there is a parameter (presence over time) that has an unknown value, and this paper provides a method to estimate this. The estimation method relies on the number of transitions from presence in the VE to presence in the real world—where these transitions are reported during the course of the VE experience. The method is far from ideal, but is, to our knowledge, the first attempt along these lines.

The new technique is introduced in the next section.

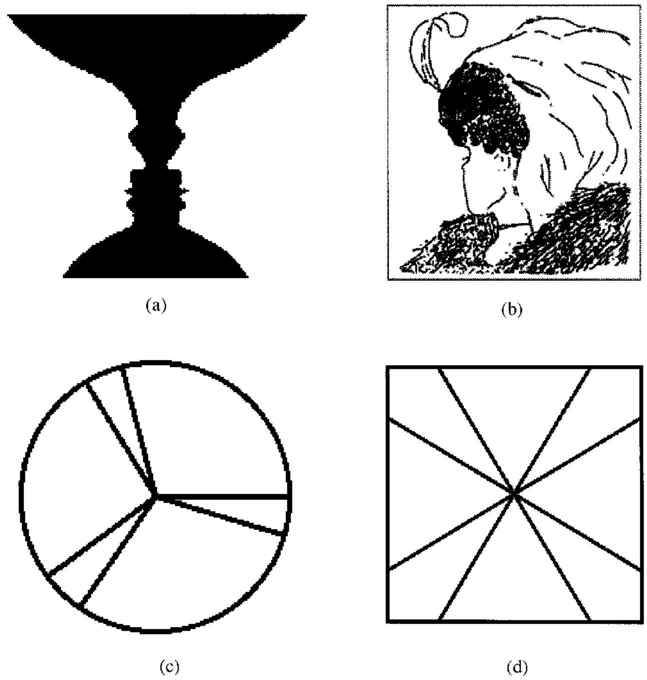

Figure 1. Gestalt images.

It is applied in an experiment in Section 4. The purpose of the experiment was two-fold: to assess whether the new measure gives results that are comparable to the usual questionnaire results, and to examine a hypothesis that the degree of body movement in a VE task is positively associated with presence. The results are given in Section 5, with discussion and critique in Section 6. The conclusions and some recommendations for future uses of the method are presented in Section 7.

3 A Presence Counter

3.1 Introduction

Gestalt psychology (Kohler, 1959) contains a notion of figure and ground: within a single figure (Figure 1a) (Perls, Hefferline, & Goodman, 1969), one aspect might come to the foreground, thus giving one interpretation, or another aspect might come to the foreground, resulting in a quite different interpretation. Just as transitions occur between figure and ground in gestalt psychology, so in VE experiences people often report such transitions between the real and the virtual.

Figure 1a through 1d are examples of the well-known result that the same information can be perceptually interpreted as quite different entities by the same person at different moments in time. Figure 1c, for example, will usually be first interpreted as three narrow triangular sectors radiating from the center of the circle. However, after staring at the center for a while, the figure will suddenly reorganize itself into something different, and then every so often a spontaneous change from one interpretation to the other will occur (Kohler, 1959).

While in an immersive VE, the participant receives a continuous stream of sensory data—mainly visual from the VE, but also often auditory from the real world, and of course real-world tactile and kinesthetic data (such as the weight of the helmet). Occasionally, the VE sensory data exhibits glitches, such as when the frame rate suddenly changes (for example, a more complex part of the scene comes into view), or when a close-up view of an object reveals its texture mapping. Occasionally, real-world data will intrude: a telephone rings, there is a sudden movement of air as a door is opened, the temperature changes, a cable wraps around a leg. Sometimes, internal mental processes of the participants will spark the realization that they are actually in a VE, or wearing a head-mounted display, really in some laboratory or exhibition hall, and not in the illusory place presented to them by the VE.

In other words, at any moment two alternate gestalts are available to the individual experiencing a VE: state V ("I am in the place depicted by the VE system"), and state R ("I am in a lab in the Computer Science building, wearing a helmet."). At each moment, the individual will tend towards one rather than the other. Presence in the VE—virtual presence—may be thought of as the extent to which the interpretation V is favored.

During the course of a VE experience, however, as suggested, an individual will typically experience transitions between states V and R. The moments at which the individual switches from one interpretation to the other—in particular, from V to R—are of particular interest. If it could be known when and why these occurred, this would be a major contribution to the problem of eliciting the factors that enhance or inhibit virtual presence. The participants cannot be asked to report transitions from R to V, because this would require them to immediately break out of their state of presence to report back to the real world. However, it is a postulate of this paper that they can be asked to report transitions from V to R.

The last point is controversial, and it is argued by analogy with common experience. Suppose you were asked, as is usual with many systems of meditation, to quiet your mind, to stop conscious thought. Many readers would have tried this. Now suppose that an additional instruction were given: At the moment you have achieved a quiet mind, report this to your meditation instructor. This is impossible for obvious reasons. However, suppose the additional instruction were, instead, as follows: You may achieve a quiet mind, but, if at any time you become aware that thoughts are once again buzzing through your head, please report this to your instructor. Now it is possible to achieve a quiet mind, and, while in such a state, the instruction to report a transition to an active mind is not in awareness (otherwise a quiet mind would not have been achieved). It is reasonable to assume that, when you become aware of conscious thoughts again, you will remember to report this transition to the instructor.

Another example is again a common experience: becoming very absorbed in a movie. While so absorbed, you are typically oblivious to your real surroundings, even oblivious to the state of your body. Every so often, though, some real world event, or some event within the movie itself will occur that will throw you out of this state of absorption and back to the real world of the theater: someone nearby unwraps a candy bar, someone coughs, some aspect of the storyline becomes especially ridiculous, and so on. The reporting of transitions into the state of absorption is impossible without undermining the absorbed state itself. However, reporting transitions back to reality are obviously possible.

Now virtual presence is being structurally likened to the quiet mind or the absorbed state in a movie. While the participant is virtually present, there is no logical requirement that they must be thinking about reporting transitions to R, for if they are thinking this then they are not (yet) in state V. It is this strong definition of virtual presence that is adopted in this paper.

A further analogy can be found in the study of dreams. A researcher in a dream research laboratory knows the likely onset of a dream by observing rapid eye movement (REM). At any moment during the REM phase, the sleeper can be awoken and asked to report the dream.[2] In the case of the VE experience, if the state of presence is considered equivalent to a dream, the dreamer is awakened by whatever caused the break in presence. At that moment, a report can be given that a break has occurred without this in itself disturbing the sense of presence, which of course has already been disturbed.

3.2 A Stochastic Model for Breaks in Presence

Consider the following scenario: An individual enters a VE with the instruction to report whenever a break in presence (BIP) occurs, and to report this only at such a moment. At the end of the experience, lasting time t, there will be b such BIPs at times $t_1, t_2, \ldots, t_b$. The problem now is to use this information to recover the tendency (p) of the individual to be in the presence state and also to understand the reasons why the BIPs occurred when they did. Here, p is given a specific interpretation as the asymptotic (long-term equilibrium) probability of being in state V. This is not particularly different from Schloerb's interpretation of subjective presence, although the method of estimation is different.

It is clearly difficult to recover p from the time sequence, because only half the information is available (that is, when and how many times there was a break in presence is known), but the times when the individual entered the presence state are unknown. When $b = 0$ (no transitions), for example, is this because the individual spent the whole time present (in state V), or the whole time in state R? For any given value of b there are two extreme possible interpretations: one in which the unknown time is assumed to be in the V state, and the other in which the unknown time is assumed to be in the R state. The discrepancy between these two interpretations decreases with increasing b. Assuming that the transitions from R to V and V to R occur instantaneously at random moments in time according to a Poisson process, it is easy to show that the expected value of p for increasing b is 0.5 (Appendix A).

An estimator for p can be constructed with some simplifying assumptions. Suppose that presence is binary; that is, at any moment of time, the participant is either in state R or state V. Discretize time by dividing the total time into n equal intervals ($t = 1, 2, \ldots, n$). Denote by p_{ij} the probability that, if at time interval t the participant is in state i, they will be in state j at the next time interval $t + 1$ (that is, a BIP has occurred on the boundary between these two time intervals). Here, state 0 corresponds to R and state 1 to V. Note that this assumes p_{ij} to be independent of t, so the transition matrix

$$P = \begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix} \qquad \text{(EQ 1)}$$

represents a stochastic process modeled by a two-state Markov chain (Karlin, 1969).

It is not difficult to show that P^k is the k-step transition matrix, its elements $P_{ij}^{(k)}$ are the probabilities that, if at time t the individual is in state i, then at time $t + k$ they will be in state j. As $k \to \infty$, the equilibrium probabilities p_0 and p_1 are obtained, denoting the probabilities of being in the corresponding states in the long run (which, given the assumptions of a Markov chain, are independent of the initial state). A fundamental limit theorem of Markov chains shows that (in the particular case of the two-state chain):

$$\begin{aligned} p_0 &= p_0 p_{00} + p_1 p_{10} \\ p_1 &= p_0 p_{01} + p_1 p_{11} \\ p_0 + p_1 &= 1, \end{aligned} \qquad \text{(EQ 2)}$$

and, therefore,

$$p_0 = \frac{p_{10}}{p_{01} + p_{10}} \qquad p_1 = \frac{p_{01}}{p_{01} + p_{10}} \qquad \text{(EQ 3)}$$

The unknown p is interpreted as p_1, the equilibrium probability of being in state V.

2. An excellent popular account of this type of research can be found in S. LaBerge's *Lucid Dreaming* (Ballantine Books, 1985).

The goal now is to use the observed data $t_1, t_2, \ldots, t_b$ to estimate the transition probabilities p_{ij} under each of two alternate conditions, the first assuming a low propensity to presence and the second a high propensity (bearing in mind the two possible interpretations of $b = 0$). In each case, the t_i are assigned to the appropriate intervals and mark a transition from state 1(V) to 0(R); such transitions are assumed to occur at the boundary between the two intervals.

3.2.1 Low-Presence Condition. There are b observed transitions from V to R (BIPs). If t is an interval at which there were such a transition, then, at interval $t - 1$, the participant must have been in state V. There are, therefore, b intervals with state V. It is assumed, for the moment, that intervals are small enough so that no two successive states reported a BIP, and that the first and last intervals did not report a BIP. In the low-presence condition, it is assumed that all intervals in which the state is unknown are in state 0.

p_{00} is the proportion of times that an interval in state 0 is followed by an interval also in state 0. There are $n - 1 - b$ intervals in state 0 that are followed by another interval. (Interval n has no successor.) All but b of them are followed by intervals in state 0. Therefore,

$$p_{00} = \frac{n-1-2b}{n-1-b} \qquad p_{01} = \frac{b}{n-1-b} \qquad \text{(EQ 4)}$$

where $2b \leq n - 1$.

p_{10} is the proportion of times that an interval in state 1 is followed by an interval in state 0. Because this always occurs,

$$p_{10} = 1 \quad \text{and} \quad p_{11} = 0. \qquad \text{(EQ 5)}$$

From these, the equilibrium probabilities are

$$p_0 = \frac{n-1-b}{n-1} \qquad \text{(EQ 6)}$$

and

$$p_1 = \frac{b}{n-1},$$

where $2b \leq n - 1$.

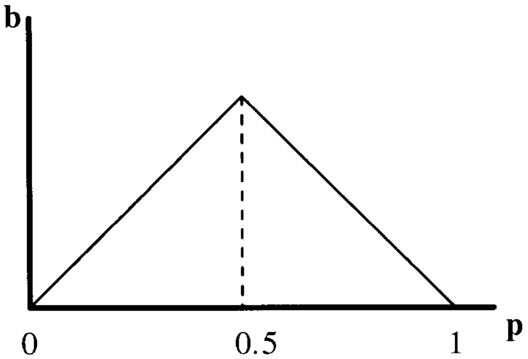

Figure 2. Relationship between number of BIPs (b) and overall presence (p).

3.2.2 High-Presence Condition. In this case, the assumption is that all intervals in which the state is unknown are in the state V(1). A similar analysis to that above yields

$$p_0 = \frac{b}{n-1} \qquad \text{(EQ 7)}$$

and

$$p_1 = \frac{n-1-b}{n-1},$$

where $2b \leq n - 1$.

Let $p_c(b)$ be the equilibrium probability of being in state V with b BIPs observed and with c corresponding to the low-presence (L) condition or the high-presence (H) condition. Then,

$$p_L(b) = \frac{b}{n-1} \qquad \text{(EQ 8)}$$

and

$$p_H(b) = \frac{n-1-b}{n-1},$$

where $2b \leq n - 1$.

The relationship is illustrated in Figure 2, showing that, when the number of BIPs achieves its maximum $(n - 1)/2$, $p = 0.5$.

Figure 2 highlights a problem: In practice, only b is observed, and, for any level of b, there are two extreme values of p. Knowing only b gives insufficient information to estimate p. To choose between $p_L(b)$ and $p_H(b)$, therefore, a discriminator is required—some additional information to select one of the two alternatives. The simplest way to achieve this is a question at the end of the session, asking the participant to classify their overall experience with respect to their sense of presence. The answer to this together with the value of b would then allow an estimate of p.

It should be recalled that this analysis gives, for any condition, two extreme interpretations. For example, in the low-presence condition, the analysis implies that

$$\frac{b}{n-1} \leq p < \frac{1}{2}. \quad \text{(EQ 9)}$$

In the absence of prior information, it would be normal to use an estimate halfway between these two bounds. Such estimates would be linear transforms of $p_L(b)$ and $p_H(b)$, and therefore would have no effect on relationships with other variables discovered in statistical analysis. Therefore, this paper continues to use $p_L(b)$ and $p_H(b)$, which should properly be referenced as "extremal probabilities," although the qualifier "extremal" is usually dropped.

3.2.3 Special Cases.

For any choice of time interval, there can always be a situation in which successive intervals report a BIP, or in which there is a BIP in the first interval or in the last interval. It is important to be able to cater for these special cases, in order to avoid the problem of having to choose very large values of n, thus forcing the probabilities to the extremes.

The analysis can be easily adjusted to take this into account. One additional assumption is made: If there are successive BIPs, then the amount of time in the V state in-between them is negligible.

Suppose that k out of the b BIPs are followed by a BIP in the next interval. Then, the transition matrix probabilities are as follows:

$$P(low - presence) = \begin{bmatrix} \frac{n-1-2(b-k)}{n-1-b+k} & \frac{b-k}{n-1-b+k} \\ 1 & 0 \end{bmatrix} \quad \text{(EQ 10)}$$

with

$$p_L(b) = \frac{b-k}{n-1} \quad \text{(EQ 11)}$$

and

$$P(high - presence) = \begin{bmatrix} \frac{k}{b} & \frac{b-k}{b} \\ \frac{b-k}{n-1-b} & \frac{n-1-2b+k}{n-1-b} \end{bmatrix} \quad \text{(EQ 12)}$$

with

$$P_H(b) = \frac{n-1-b}{n-1}. \quad \text{(EQ 13)}$$

A further refinement allows for a BIP in the first or last intervals. Let $s_1 = 1$ if there is a BIP in the first interval and 0 otherwise, and, similarly, $s_n = 1$ if there is a BIP in the last interval and 0 otherwise. Then, following the same reasoning above, it can be shown that the transition matrix probabilities are

$$P(low - presence) = \begin{bmatrix} \frac{n-1-2(b-s_1-k)}{n-1-(b-s_1)+k} & \frac{b-s_1-k}{n-1-(b-s_1)+k} \\ 1 & 0 \end{bmatrix} \quad \text{(EQ 14)}$$

and

$$P(high - presence) = \begin{bmatrix} \frac{k}{b-s_n} & \frac{b-s_n-k}{b-s_n} \\ \frac{b-s_1-k}{n-1-(b-s_n)} & \frac{n-1+k-2b+s_1+s_n}{n-1-(b-s_n)} \end{bmatrix}. \quad \text{(EQ 15)}$$

Clearly $b > k$, and, when $b = 0$, then $k = 0$, $s_1 = s_n = 0$, and the probabilities would be 0 or 1 in this case.

Figure 3 illustrates the ideas of this section. It shows

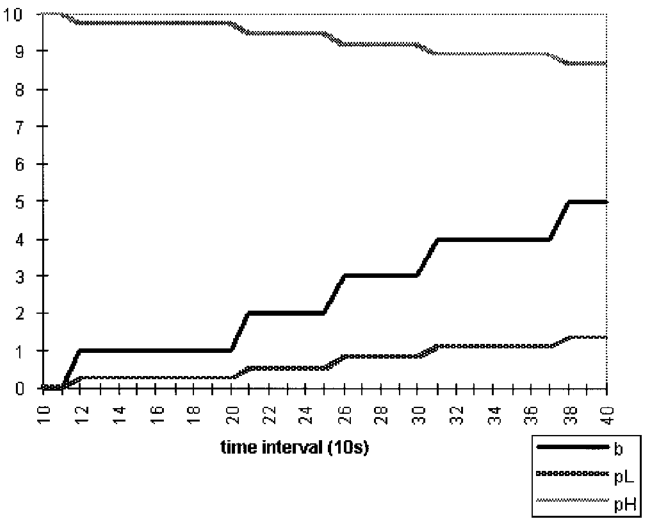

Figure 3. A time sequence showing occurrences of BIPs and the corresponding probabilities for one subject.

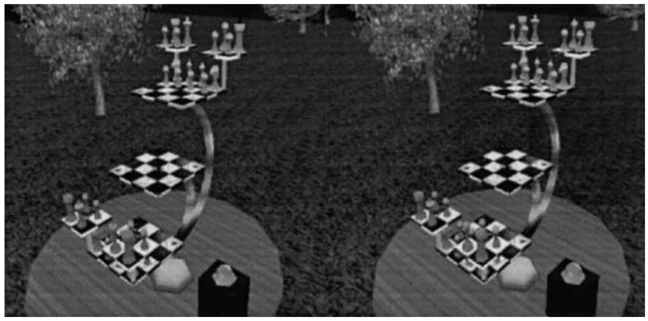

Figure 4. A stereo pair showing the 3-D chess model.

Table 1. Three-Dimensional Chess Dimensions

Object	Dimension (m)
Table top	0.74
Large chess boards	0.2 × 0.2
Small chess boards	0.1 × 0.1
Lowest board: height above table top	0.22
Middle board: height above table top	0.42
Highest board: height above table top	0.62
Small boards: height above large board	0.1

the occurrences of the BIPs and the corresponding low and high extremal probabilities (multiplied by 10) for a particular individual selected from the subjects in the experiment described in Section 4. The BIPs are taken as occurring on the boundaries between intervals, but they actually occur within an interval. This is illustrated in the graph by the steeply sloping lines in an interval in which a BIP has occurred.

4 Experiment

This section describes an experiment that had two principal goals. First, the above technique is used to estimate p. If the approach is sound, then there should be a significant positive correlation between p and postexperimental questionnaire results relating to presence, following the hypothesis that these questions are answered on the basis of the balance of time that a participant spends in the V state compared to the R state. Second, previous results (for example, Slater et al. (1998) and Usoh et al. (1999)) suggest a positive relationship between the degree of body movement of participants and their reported presence. The experiment also examines this idea in a different context to those previous studies.

The experimental scenario involved the participants observing a sequence of moves on a three-dimensional chess board (as introduced by the *Star Trek* TV series), which was chosen because it is a quite large and complex three-dimensional object and fitted well with the requirement to induce significant body movement in participants who were required to reach out and touch the chess pieces. A stereo pair of the three-dimensional chess board is shown in Figure 4. As can be seen, it is a structure with several layers, resting on a table. The dimensions are shown in Table 1.

The pieces that had to be touched were distributed over the entire board. Hence, the highest piece was approximately 1.46m above the ground, which for some subjects required considerable stretching to reach. It is important to note that the measure of body movement used (namely the total amount of hand movement) is, of

Table 2. Factorial Design

	Low activity	High activity
Number of subjects	10	10

course, a measure of whole body movement, because it would encompass such reaching and stretching.

The factorial design was for twenty participants divided into two groups, as shown in Table 2.

Each subject was paid £5 (about $9) for completing the study, and were recruited through advertisements on the campus. In the event, two subjects were unable to either understand or properly follow the instructions and were replaced by two other subjects, so 22 people completed the experiment, with two cases being discarded. The final twenty comprised eighteen men and two women: five undergraduates, six Masters students, four PhD students, two research assistants, one faculty member, and two miscellaneous others. No subject had any knowledge of, or anything at all to do with, the research itself.

Each participant started the experience in a virtual laboratory (the virtual anteroom). After receiving instructions, the participants made their way through a door to a field with trees and plants outside. Some five meters beyond the door was a table with the 3-D chess board (Figure 5 and 6). Those assigned to the Low Activity group were told to repeatedly look for a red chess piece and, when it was found, to press a button on a 3D mouse that they were holding throughout, and to observe the movement of the piece. Those assigned to the High Activity group were told that, when they observed the red piece, to reach out with their hand (holding the 3-D mouse) and touch it, and it would then move. At the end of an entire sequence of nine moves, a large button on the side of the virtual table would turn red. The Low Activity group had to click the physical button on their handheld 3-D mouse, and the High Activity group had to reach and touch the virtual red button. All participants were told that, when they noticed that the sky had become dark, they should return from the field to the starting room. The sky was darkened after three complete sequences of moves, and the mean and standard deviation of the time spent in the field was 319 sec. ± 64 sec. All subjects were told that they would be asked about the sequence of moves observed after the experience.

Figure 5. View from within the virtual lab out to the field.

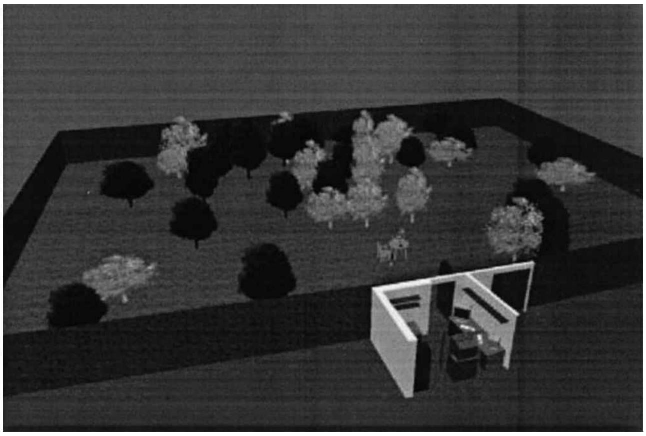

Figure 6. Overview of the lab area.

Prior to starting the experiment, all subjects were asked to complete a short questionnaire that obtained

Table 3. Transition-to-Reality Instructions

IMPORTANT: Transition to Reality
When you enter the virtual reality you may have the sense of being in "another place."
In just the same way as you saw transitions in the images that you just looked at, you may experience transitions in your sense of place—
Virtual: sometimes you will be in the virtual place
Real: sometimes you will become aware of the real lab in which the experience is really happening.
If and only whenever you experience a **transition to Real,** please say "*Now*" very clearly and distinctively.

Figure 7. Exocentric view of someone reaching out to touch a chess piece.

background information: gender, job status, and prior experience of virtual reality.

After completing the questionnaire, the subject was shown each of Figure 1b through 1d in turn. (Because most subjects had seen Figure 1b before, it was hardly used.) They were asked to describe their initial interpretation of the figure. (For example, for Figure 1c, most saw the three thin triangles first.) Then they were asked to stare at the figure and notice if any change occurred. If a change did happen, they were asked to continue to observe the figure and clearly exclaim "Now" if and whenever it spontaneously reconfigured itself to look the same way as when they first saw it. After this training, they were given the instructions in Table 3 to read.

All instructions were reinforced verbally once the subject entered the real laboratory itself, and then again while they were in the virtual anteroom, before entering the field that contained the chess board. While in the anteroom, they were shown how to move around, how to make a small red cube on a table respond by either touching it (High Activity group) or by clicking with their forefinger on the 3-D mouse (Low Activity group).

The virtual reality laboratory is in a small enclosed room within a large laboratory, in which there is continual noise (constant noise of workstations, and random noise of occasional phone rings or conversations). No attempt was made to reduce background noise or to further isolate the VR room from the remainder of the laboratory: indeed, there was interest as to whether the background events would trigger transitions from V to R.

The scenarios were implemented on a Silicon Graphics Onyx with twin 196 MHz R 10000, Infinite Reality Graphics with 64M main memory. The software used was Division's dVS and dVISE 3.1.2. The tracking system has two Polhemus FASTRAKs, one for the HMD and another for a five-button 3-D mouse. The helmet was a Virtual Research VR4 which has a resolution of 742 × 230 pixels for each eye, 170,660 color elements, and a field of view of 67 deg. diagonal at 85% overlap.

The total scene consisted of 13,298 polygons running at a frame rate of no less than 20 Hz in stereo. The latency was approximately 120 ms.

Subjects moved through the environment in gaze direction at constant velocity by pressing a thumb button on the 3-D mouse. They had a simple inverse kinematic virtual body (Figure 7). When they reached forward to touch a chess piece, they would see their virtual arm and hand.

At the end of the session, subjects were given a second questionnaire, the main purpose of which was to gather information on their sense of presence. An initial question asked for the reason why (if this was the case) they reported no or very few transitions, giving four options: rarely being in the virtual world, almost always being in the virtual world, forgetting to report transitions, or other reasons. In retrospect, this question was not particularly useful, because it required an answer only when subjects reported no or very few transitions, without giving a definition of this. No subject reported forgetting the instruction to report transitions.

A second question was open-ended, asking for the causes of the transitions (whether or not these had been reported at the time). Five questions related to presence were interspersed throughout the questionnaire, each rated on a scale of 1 to 7, where 1 indicated low presence and 7 high presence. These questions followed the same model introduced by Slater, Steed, and Usoh (1993) as briefly discussed in Section 2. The first question was a priori considered the most direct elicitation of presence and used as the discriminator: a score of more than 4 on this resulted in the formula $p_H(b)$ being used, otherwise $p_L(b)$.

The five questions relating to presence were:

1. Please rate *your sense of being in the field*, on the following scale from 1 to 7, where 7 represents your *normal experience of being in a place.*
   I had a sense of "being there" in the field:
   (1) Not at all. (7) Very much.
2. To what extent were there times during the experience when the field became the "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?
   There were times during the experience when the virtual field became more real for me compared to the "real world" . . .
   (1) At no time. (7) Almost all the time.
3. When you think back about your experience, do you think of the field more as images that you saw, or more as somewhere that you visited? Please answer on the following 1 to 7 scale:
   The virtual field seems to me to be more like. . .
   (1) Images that I saw. (7) Somewhere that I visited.
4. During the time of the experience, which was strongest on the whole, your sense of being in the field, or of being in the real world of the laboratory?
   I had a stronger sense of being in . . .
   (1) *The real world of the laboratory.* (7) *The virtual reality of the field of plants.*
5. During the time of the experience, did you often think to yourself that you were actually just standing in an office wearing a helmet or did the field overwhelm you?
   During the experience I often thought that I was really standing in the lab wearing a helmet . . .
   (1) *Most of the time I realized I was in the lab.* (7) *Never because the virtual field overwhelmed me.*

Some data were automatically collected during the course of the experiment, in particular the times at which the participant said "Now" and the total time in the virtual field. The amount of hand and head movement was computed by the program running the simulation as a function of the head and hand tracking.

5 Results

5.1 General

The overall levels of reported presence as ascertained from the questionnaire responses were high. Figure 8 shows the median response for each of the five presence-related questions, showing, for example, that on question 1 (the discriminator), half of the responses were at level 5 or higher.

The number of BIPs ranged between 0 and 14. The mean time between BIPs was 48 sec. $\pm$ 37 sec., the minimum time interval was 5.5 sec. and the maximum 141 sec. The time interval used for the analysis was 10 sec., this being approximately the largest compatible with the assumptions that $2b \leq n - 1$. There were two cases where there were some BIPs in sequence, and two other cases where there was a BIP in the first or last interval.

The questionnaire-based presence, using all five presence questions, is plotted against the number of BIPS, in Figure 9.

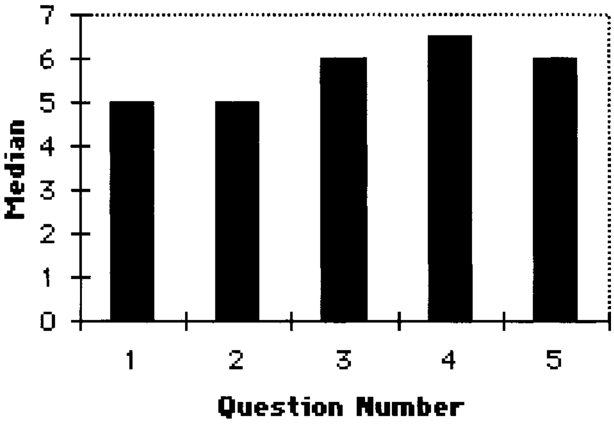

Figure 8. Median levels of reported presence.

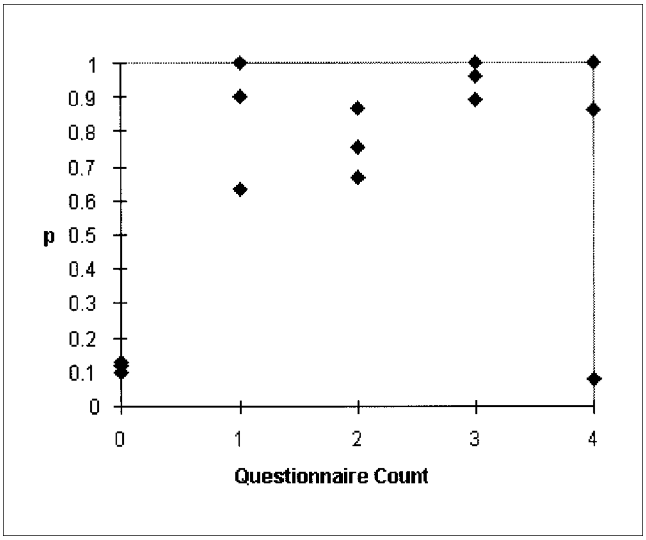

Figure 10. Scatter plot of p against Questionnaire Presence.

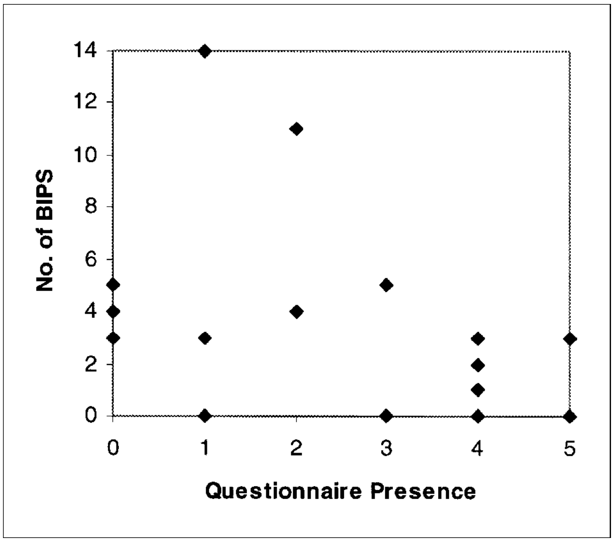

Figure 9. Number of BIPs by Questionnaire Presence.

5.2 Relationship between p and Questionnaire Based Presence

The first question to consider is whether a relationship exists between the estimate of presence p, and the questionnaire responses. The usual approach of the authors to combining the results of the presence questions into one overall score (without resorting to averaging across ordinal data) is to count the number of high scores (6 or 7), thus giving each subject a count out of 4, for the questions other than that used as the discriminator (questions 2 to 5 above).

Figure 10 shows the scatter plot of p against the questionnaire presence count (recall that the p's are extremal). There is a clear positive relationship, although with one outlying point. Even including this point, there is a statistically significant correlation between p and the presence count ($r^2 = 0.32$, $t = 2.920$, $t_{18} = 2.101$ at the 5%-significance level). When this outlier is removed, the result improves substantially ($r^2 = 0.65$, $t = 5.588$, $t_{17} = 3.965$ at 0.1%). Examining the responses of the particular person represented by the outlier, he wrote that he was disturbed by the absence of sound in the VE, knew that the experimenters were in the real lab alongside him, and that he wanted to talk to them because exploring an environment is often a "communal activity." The experimenter's notes record that he did indeed continue to talk to them during the immersive experience. He gave a response of 3 to the discriminator question (writing "SOUND!" next to his response), and scores of 7 for each of the remaining four presence-related questions. The assignment of this person to the low-presence condition on the basis of this particular discriminator is therefore dubious.

Table 4. Means and Standard Deviations for p by Activity

	Mean and standard deviation
Activity High	0.60 ± 0.44 ($n = 10$)
Activity Low	0.89 ± 0.12 ($n = 10$)
	$t = 1.99$
	($t_{16} = 2.120$ at 5%)

5.3 Relationship between p and Hand Activity

The next issue to consider is the relationship between p and the main independent factors. Table 4 shows the means and standard deviations of p for the activity groups, and the difference in means is not significant although contrary to expectation: the Low Activity group seems at first sight to have a higher average presence than the High Activity group. There is a highly significant difference in variance (the variance ratio is 14.0, $F_{9,9} = 3.2$ at 5%), with much less variation among the Low Activity group. The difference in variation was to be expected, because the subjects in the inactive group were not required to move their hands at all (except to press the button on the handheld 3-D mouse for navigating, which, in fact, did not require any movement of the hand relative to the body).

A more detailed examination reveals a different situation, showing that the differences in means cannot be taken at face value. Figure 11 shows a scatter plot of p by total hand movement per unit time, discriminating between the two activity groups. It suggests that there is no discernible relationship between the amount of hand movement of the Low Activity group and p, as would be expected. However, for the High Activity group, there is a positive linear relationship between hand movement and p. Therefore, comparing raw means for the two groups, not taking into account the hand movement, is anyway invalid.

Table 5 gives the result of a multiple regression analysis of p on activity and hand movement (HM), allowing for the possibility of differing slopes for the Low Activity and High Activity groups. There is a significant positive slope for the High Activity group, with an overall squared multiple correlation of 0.38.

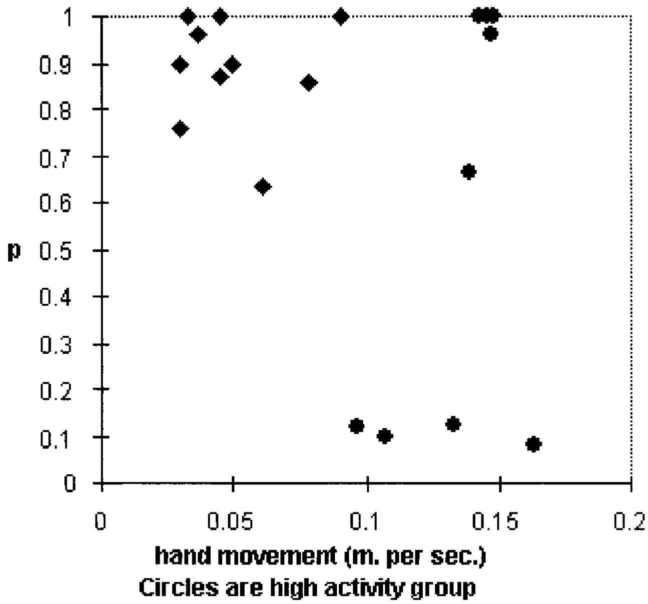

Figure 11. Presence against hand movement.

Table 5. Regression of P on Activity and Hand Movement per Unit Time (HM)

Activity	Regression	t for slope
High	$p = -0.91 + 11.07$ HM (s.e. = 4.90)	2.26
Low	$p = 0.87 + 0.34$ HM (s.e. = 4.78)	0.07 (n.s.)

Allows for different slope for HM for each level of activity. Based on $n = 20$ observations, with d.f. = 16, $t_{16} = 2.120$ at 5%. Overall $R^2 = 0.38$.

Inspection of Figure 11 shows an outlying point, with a low presence and high hand movement (above 0.15 mps) in the High Activity group. This was caused by the same person who was the outlier in Figure 10. Removing the data for this person from the analysis results in Table 6. The squared multiple correlation increases to 0.73, and the slope for the High Activity group is well into the highly significant range.

5.3.1 Explanations for BIPs. One question asked the participants to give the reasons for their transi-

Table 6. Regression of p on Activity and HM (Outlier Removed)

Activity	Regression	*t* for slope
High	$p = -1.90 + 19.11$ HM (s.e. = 3.36)	5.69
Low	$p = 0.87 + 0.34$ HM (s.e. = 2.92)	0.11 (n.s.)

Based on $n = 19$ observations, with d.f. = 15, $t_{16} = 2.131$ at 5%. Overall $R^2 = 0.73$.

tions to the real: *If you did make transitions from virtual to real, whether or not you reported these at the time, what do you remember as the causes of the transitions? (For example, hearing an unexpected noise from the real lab might cause such a transition.)*

The reasons given can be classified into two main types:

External—Sensory information from the real world intruded into or contradicted the virtual world, either in the form of noises or people talking, or else the touch or feel of interactions with real solid objects (such as the VR equipment itself).

Internal—This is where something "wrong" with the virtual world itself is noticed, such as the laws of physics not being obeyed, objects looking unreal, the absence of sounds, or display lag.

There were a number of subsidiary reasons:

Experiment—Some aspect of the experimental set-up itself, or the instructions intruded.

Personal—Some personal feeling intruding, such as embarrassment or consciousness of being observed from the outside.

Attention—A loss of attention to what is happening in the virtual world, or some aspect of the virtual world that results in a loss of presence.

Spontaneous—A BIP for no (conscious) apparent reason.

Table 7 gives the number of participants who responded in each of these categories and some examples of each.

5.3.2 The Discriminator Question. The analysis above hinges on the choice of the discriminator question, because it classifies each participant into a low-presence or high-presence group, and therefore determines the computation of p. A different discriminator question could lead to quite different results. However, the results for this experiment are robust with respect to the choice of discriminator question.

The analysis was repeated for each of the remaining four presence-related questions, and also for the average of all of the five questions (Table 8). (Of course, the outlying point corresponding to someone who had written 3 for question 1, but 7 for each of the others, does not occur for any of the choices of discriminator other than question 1.) For every choice of discriminator question, except for question 3, the results are the same. When the mean response of all of the presence questions is used as discriminator, the results are again the same. (Note that question 4 has exactly the same impact as a discriminator as the average.)

6 Discussion

The method presented in this paper relies on a number of assumptions.

1. **Presence in the "real" and "virtual" is treated as a binary state.** The authors would not seek to defend this as a statement about the psychological processes involved. It is used here in the spirit of a simplifying assumption, to allow the construction of the stochastic model. However, arguments were presented at the conclusion of Section 2 in favor of the notion that presence may be considered as a selection of one environment relative to which an individual acts at a given moment.
2. **The stochastic model assumes discrete time.** Again this is a simplifying assumption that is often employed in the initial stages of constructing a model of complex phenomena. It may be possible to employ a continuous-time stochastic model instead.

Table 7. Reasons Given for Transitions to the Real

Cause	*n*	Some examples
External sound	7	"Noises from the lab (people talking)."
		"Hearing background noise."
External touch or force	9	"I was supposed to be in a grass plain, but when I moved my feet I realized it was a plank under my feet (in the real)."
		"Feeling of the floor under my feet."
		"Becoming aware of cable wrapped around foot."
		"The cable brushing against my legs."
		"Trapped in wires."
Internal	1	"The length of time taken to interact with the world."
	1	"Turning and thus becoming aware that the virtual world was not the real world."
		"If moved head quickly."
		"The time taken for the chess pieces to move."
		"The way the sky darkened, not smooth, like someone had switched off the sun."
		"Weird things happening that are obviously not real (e.g., the chess set)."
		"The more I needed to examine the contents of the 'virtual' the more my awareness flipped into the 'real.' "
		"Became very close to the chess board."
		"Getting too near to things (especially trees)."
Experiment	3	"Having to remember the real-world instructions."
		"The task of being asked to monitor the changes from virtual to reality itself creates a sense of going back to reality."
		"Once experienced a transition, became sensitive to it happening again."
Personal	3	"Wanted to talk to the experimenters to share the experience."
		"Embarrassment."
		"Very conscious."
Attention	3	"Transitions occurred between the tasks, for example, when looking for the next red piece, but only if I couldn't see it at first glance."
		"Attention wandered after realizing that the chess sequence was iterative."
		"Not having a task to do."
Spontaneous	2	"Spontaneous feeling."
		"It just occurred to me."

n is number of participants who gave responses in the corresponding category.

3. **The transitions can be modeled as a Markov chain.** This assumes that the transition probabilities are one-step, that what happens in any interval is statistically independent of all other intervals except for the last. The veracity of this assumption is unknown, and again should be viewed as a simplification for the purpose of constructing an initial model.

4. **The requirement to report BIPs does not in itself influence the participants to report BIPs.** Experimental evidence supports the argument that the requirement to report BIPs increases the chance of BIPs occurring. Girgus, Rock, and Egatz (1977) found that giving subjects a knowledge of the reversibility of ambiguous figures substantially

Table 8. Regression Analysis p on Hand Movement (HM) Computing p with different discriminators. Only the High Activity equations are shown (no Low Activity result is significant). n = 20, d.f. = 16, t_{16} = 2.120.

Question used as discriminator	R^2	Regression: p =	*t*-value
1. Please rate *your sense of being in the field,* on the following scale from 1 to 7, where 7 represents your *normal experience of being in a place.*	0.38	−0.91 + 11.07 HM	2.26
2. To what extent were there times during the experience when the field became the "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?	0.42	−1.64 + 17.00 HM	3.41
3. When you think back about your experience, do you think of the field more as images that you saw, or more as somewhere that you visited?	0.26	−0.23 + 7.78 HM	1.46
4. During the time of the experience, which was strongest on the whole: your sense of being in the field, or of being in the real world of the laboratory?	0.77	−1.46 + 16.23 HM	7.01
5. During the time of the experience, did you often think to yourself that you were actually just standing in an office wearing a helmet or did the field overwhelm you?	0.43	−1.64 + 16.67 HM	3.20
Discriminator is computed as average of responses to questions 1 through 5.	0.77	−1.46 + 16.23 HM	7.01

increased the chance of these being reported. Approximately half the subjects who were not told about the reversibility of figures never reported a transition, whereas all of the subjects who were told about the reversibility always reported transitions. This raises the possibility that more BIPs were reported than would otherwise have naturally occurred.

This is a difficult issue, because it could also be argued that the requirement to report BIPs sets up a dual task for the participants: to do their actual task in the VE and to pay attention to their state in order to be able to report the BIPs. A counterargument to this is that the requirement to report a BIP is likely to enter consciousness only at the time immediately after a BIP has occurred (as discussed earlier).

A preferable response to these problems is to agree that the method for reporting BIPs—relying on a verbal response—is certainly not an ideal way to obtain this information. It is an interesting and challenging research topic to try to find physiological correlates to BIPs that can be measured unobtrusively.

5. **The discriminator question can discriminate between the low- and high-propensity cases.** Use of a discriminator question does indeed result in an uncomfortable reliance on questionnaire data. An alternative, behaviorally based discriminator, would be preferable.

7 Conclusions

Notwithstanding the critique above, a new method for measuring presence in virtual environments has been introduced, in which the major component of the measure depends on data collected during the course of the VE experience itself. It is based on the number of transitions between the state of being in the VE to the state of being in the real world. Using the simplifying assumption that changes in state between presence and nonpresence to form a time-independent Markov chain, an equilibrium probability of presence can be estimated. This requires only one additional postexperimental discriminator question concerning each participant's assessment of whether they had been in the presence state for more or for less than half the time.

This new technique was tried in an experiment to assess the impact of body movement on presence, and it was found to be positively and significantly correlated with the usual questionnaire-based measure. It is encouraging that the questionnaire score and the new measure were correlated. However, further studies are necessary for validation.

Another issue for the experiment, apart from the methodology for presence measurement, was the relationship between presence and hand movement. (In this experiment, head and hand movement were significantly correlated: $r^2 = 0.54$, $t = 4.6$, $t_{18} = 2.101$ at 5%). The evidence strongly suggests a positive association between presence and hand movement, in line with previous evidence on the relationship between presence and body movement. The direction of causality is unknown, but the authors suspect that there is a two-way relationship: high presence leads to greater body movement, and greater body movement reinforces high presence. There is some evidence to support the first part of this statement. Because subjects in the High Activity group were all required to reach out and touch the chess pieces, why is there such high variation in their measured hand movements, since they all had to reach the same distances? The variation can be explained by the fact that some subjects took the most-direct routes to the chess pieces, ignoring collisions with the board and other pieces, whereas others acted more as they would have in real life, avoiding collisions with other objects. Hence, it could be argued that presence in the VE caused them to act this way, thus leading to greater body movement.

The relationship between presence and body movement follows from the notion that one of the most important determinants for presence is the requirement for a match between proprioception and sensory data. This is consequential for the design of interaction paradigms, where semantically appropriate body movement, exploiting proprioception, is preferred, for example, to the importation of techniques from 2-D interfaces. This relationship between presence and proprioception in the design of interaction paradigms has been exploited in several studies (Slater, Usoh, & Steed, 1995; Mine, Brooks, & Sequin, 1997; Grant & Magee, 1998; Usoh et al., 1999).

We suggest some recommendations for future use of the new measure. First, the discriminator question should ask for the information that is required in a very direct manner. (Question 4 would have been preferable to question 1.) As soon as the VE experience has terminated, the participant should be asked to estimate the overall proportion of time spent in the presence state, crucially whether above or below 50%. The exact wording of this discriminator question, or indeed as noted in Section 6, whether there is some better way to obtain this information, should be given more thought.

Second, a standard time interval should be agreed, so that results can be easily compared between different applications and systems. In this experiment, the time interval was chosen to be the greatest compatible with the requirement that $2b \leq n - 1$ (n is the number of intervals). The interval used was 10 sec. The choice of large values of n grants undue weight to the statistical significance of the count data, and pushes the probability estimates to more-extreme values (although it does not alter the relationship between them).

The results are nevertheless robust with respect to the range of time intervals. An analysis with intervals ranging from 1 sec. through to the maximum compatible with the crucial requirement of $2b \leq n - 1$ always gives the same results. A preferable solution would be to construct a model that does not require the use of discrete time intervals.

Finally, to return to the issue of body movement. In the 3-D chess experiment, it is clear that many of the (active) subjects are learning about the chess board with their whole bodies. As stated earlier, to call the movements "hand movements" is an understatement of what is being measured. It is not surprising that, among the active group, those who exhibited greater body movement also tended to have a greater sense of being in the same space as the 3-D chess board.

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Appendix A. The Expected Time ``Present'' as the Number of BIPs Increases

Consider the transitions from R to V and V to R as occurring instantaneously at random moments in time according to a Poisson process; that is, each time interval is an independent exponentially distributed random variable. The result is the same and mathematically simpler if everything is normalized by the total time, leading to $2b$ observations from the uniform probability distribution on the interval $\{0, 1\}$. Suppose the BIPs occur at times $t_2, t_4, \ldots, t_{2b}$. The times at which the transitions R to V occur are $t_1, t_3, \ldots, t_{2b-1}$, with $0 < t_1 < t_2 < \ldots < t_{2b}$. Therefore, the total time in the state V, T_V is given by the formula

$$T_V = \sum_{i=1}^{i-b} (t_{2i} - t_{2i-1}). \qquad \text{(EQ 16)}$$

The expected value of t_i is $i/(2b + 1)$, resulting in

$$E(T_V) = \frac{b}{2b + 1} \qquad \text{(EQ 17)}$$

Therefore,

$$\text{as } b \rightarrow \infty, \quad E(T_V) \rightarrow \frac{1}{2}. \qquad \text{(EQ 18)}$$

In the time interval from t_{2b} to 1, there may be another transition from R to V. However, the expectation of this extra time in V will tend to 0 with increasing b.