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The Influence of Passive Haptic Feedback and Difference Interaction Metaphors on Presence and Task Performance

Abstract

This paper explores the influence of passive haptic feedback on presence and task performance using two important interaction metaphors. We compared direct interaction with the user's hand with interaction using a stylus. Twenty-four participants performed a simple selection task consisting of pressing buttons while playing a memory game, with haptic feedback and interaction metaphor as the independent variables. We measured task performance by computing errors and time between button presses. We measured presence with questionnaires and through a new method based on users' involuntary movements. Our results suggest that passive haptic feedback improves both presence and task performance. However, small but significant differences related to the interaction metaphor were only apparent when haptic feedback was not provided.

1 Introduction

Virtual reality (VR) has become a powerful tool that can model complex environments. However, more research is needed to gain a better understanding of *interaction mechanisms,* design techniques that allow participants to interact with objects in a virtual environment (VE). Specifically, the interaction metaphor (i.e., directly touching an object with a hand compared to using a stylus) and the presence or absence of feedback are key issues that may influence both task performance and presence. This paper reports an experimental study to assess these variables during a simple selection task. Our goal is to suggest design principles for three-dimensional VR interfaces.

In this research, the feeling of being in a virtual place or the sense of presence is derived from two definitions. First, Witmer and Singer (1998, p. 227) define presence as: "the psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences." Second, Lombard and Ditton (1997, p. 7) define presence as "the perceptual illusion of non mediation." In other words, presence is what happens when participants forget that their perceptions are being mediated by technology.

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The sense of presence is influenced by interaction mechanisms (Bowman, Johnson, & Hodges, 2001; IJsselsteijn, 2002; Navarre et al., 2005). When interacting with the physical environment, action and perception are integrated in the perceptual-motor loop. This process, combined with other cognitive and emotional variables, can determine sense of presence and impact the resulting task performance. Therefore, this interaction has two main qualities that must be considered: first, the nature of the multisensory stimuli, and second, how the user can perform actions within the environment. We included these factors in our study as independent variables. We considered two different interaction techniques or metaphors (direct selection with the hand and indirect selection with a stylus) with two different feedback conditions (with and without haptic feedback).

There is a controversy in the literature about the existence of a direct link between presence and task performance. Most of the studies support the idea of a positive correlation between presence and task performance (Bailey & Witmer, 1994; Ellis, Dorighi, Menges, Adelstein, & Jacoby, 1997; Lin, Duh, Abi-Rached, Parker, & Furness, 2002; Maida, Aldridge, & Novak, 1997; Pausch, Proffitt, & Williams, 1997; Singer, Allen, McDonald, & Gildea, 1997; Singer, Ehrlich, Cinq-Mars, & Papin, 1995). However, up to now, the evidence has been mixed (Bormann, 2006; Mania, Chalmers, Troscianko, & Hawkes, 2000; Welch, 1999). Indeed, Ellis (1996) reported that for certain tasks, a lower level of presence may imply better performance.

Haptic feedback in VR has mainly been provided through devices that provide active programmable forces. We refer in this paper to this type of feedback as active haptic feedback. These applications usually require that the user interact by holding a device or a tool. Exactly how the interaction metaphor used in these devices influences the user experience within the virtual environment is not fully understood. Moreover, it is much more difficult and requires very complex devices to provide active haptic feedback when users make selections directly with their hands. Therefore, in our experiment we have chosen to use only passive haptic feedback.

In the current study, we use the term "passive haptic" to refer to feedback provided in the context of passive haptic constraints. This technique is based on augmenting graphical cues with surrounding physical cues. In particular, we implement these haptic constraints with a physical prop. When interacting using a stylus, we have used exactly the same passive haptic feedback, in order to keep both conditions comparable.

1.1 Background

1.1.1 Haptic Feedback, Presence, and Task Performance. The influence on task performance and the sense of presence of sensory information perceived by users within a VE is a topic that has been addressed by many researchers. Certain studies have focused on the role of visual and auditory stimulation and their influence on presence and task performance (Hendrix & Barfield, 1996a, 1996b), finding that the addition of stereoscopic cues and spatial sound improved spatial realism and yielded sensations of improved presence. Other studies have also pointed out the importance of visual and auditory cues in improving both task performance and presence (Biocca, Inque, Polinsky, Lee, & Tang, 2002; Popescu, Burdea, & Trefftz, 2002).

The development of force feedback devices has motivated the study of how the haptic modality influences task performance and presence (Wall, Paynter, Shillito, Wright, & Scali, 2002), along with its use as a design element for human-computer interaction (MacLean, 2000). Sallnäs, Rassmus-Gröhn, and Sjöström (2000) found that haptic feedback significantly improves task performance and perceived virtual presence in collaborative distributed environments. All these studies used active haptic feedback and the interaction was with a stylus (tool metaphor).

Passive haptic feedback in a VE has also been implemented in several systems (Borst & Volz, 2005; Hinckley, Pausch, Goble, & Kassell, 1994; Liere, Martens, Kok, & Tienen, 2005; Insko, 2001). Moreover, different studies have assessed the effectiveness of passive haptic feedback using both objective and subjective measures. Meehan, Insko, Whitton, and Brooks (2001) found positive results in the sense of presence assessed through physiological measurements due to the addition of passive feedback on the edge of a virtual cliff. In addition, Lindeman, Sibert, and Hahn (1999) studied a task involving the manipulation of interface widgets in a VE, and found that augmenting a visual object with a physical haptic paddle improved task performance.

Other researchers have investigated the effects of passive haptic feedback provided by a real object that supplements a virtual object. Lok, Naik, Whitton, and Brooks (2003) performed a study that investigated how handling real objects affects performance and sense of presence in the context of a manual spatial cognitive task. Their results showed better task performance under haptic feedback conditions. Hoffman (1998) reported an experiment in which participants were asked to predict the properties of other virtual objects they saw but did not interact with via haptic feedback in the VE. Better results were apparent when haptic feedback was provided than without haptic interaction.

Passive haptic feedback has also been evaluated when accompanied by active feedback. Rosenberg and Brave (1996) showed, in a pilot study, that both active and passive force feedback may be effective in decreasing the task completion time for tasks that require users to position a cursor over a given target. Furthermore, the work of Borst and Volz (2003) showed that the addition of passive haptic feedback improved human performance and led to increased subjective ratings of presence during interaction with a virtual control panel using an active haptic device.

Different metaphors have been proposed for supporting the implementation of the main selection techniques provided within a VE (Bowman & Hodges, 1997; Pierce, Stearns, & Pausch, 1999; Poupyrev, Billinghurst, Weghorst, & Ichikawa, 1996). The metaphors more widely implemented are (1) a virtual hand that maps movements of the participant's hand in movements of a virtual object; (2) ray casting based on tracing an intersection ray used to select objects with a direction given by the user viewpoint and the point signaled by the hand; (3) go-go metaphor that extends the selection area of ray casting techniques by growing the participant's arm as if it were elastic; (4) voodoo dolls metaphor that creates copies or dolls of virtual objects that can be handled by participants.

All the aforementioned passive haptic feedback systems used the virtual hand metaphor, as researchers widely believe that direct interaction using the hands is more natural than interaction using tools. Evaluations of differences between interaction metaphors have been made by investigating selection techniques (natural hand, ray casting, go-go, the voodoo dolls, etc.) or by exploring the use of different devices (gloves, keyboards, paddles, and haptic devices), considering mainly task performance metrics. Nevertheless, less attention has been paid to passive haptic feedback and the selection metaphor used attending to the elicited sense of presence.

1.1.2 The Role of Interaction in Presence. From a theoretical point of view, many authors consider interaction to be a basic component of presence. Indeed, Witmer and Singer (1998) consider that several control factors directly related to interaction underlie the concept of presence. Furthermore, these researchers have established that "Individuals will probably experience a greater sense of presence in an environment if they are able to anticipate or predict what will happen next" (p. 229), which may also be related to coherent interactions.

Lombard and Ditton (1997) defined presence as "the perceptual illusion of non mediation," following the theory of Loomis (1992). Loomis, in this work, associated presence with the phenomenon of distal attribution and included in the model of sensorimotor interaction the effect of effectors extensions, such as the devices used in VR. This point of view is specifically focused on interaction and whether a user feels that there is a set of devices mediating their interaction with a VE. Moreover, some researchers (Büscher, O'Brien, Rodden, & Trevor, 2001; Flach & Holden, 1998; Zahorik & Jenison, 1998) have based their understanding of presence on Gibson's ecological approach to perception (Gibson, 1979). According to this theory, the sense of presence is proportional to the actions that the environment allows the user to accomplish. Therefore, the relation between perception and action is a key element for VR design.

For a thorough review of the components of presence, see Schubert, Friedmann, and Regenbrecht (1999).

Empirical research regarding interaction and presence has primarily focused on the influence of sensory information provided as interaction feedback on the elicited sense of presence. Hecht, Reiner, and Halevy (2006) evaluated mental processing times during a 3D writing task, under unimodal, bimodal, and trimodal sensory conditions, providing auditory, visual, and haptic stimulation. Their results suggested that trimodal and bimodal modalities were significantly better than unimodal conditions.

Other studies have focused on different interface characteristics. Ma and Kaber (2006) analyzed differences in the elicited sense of presence, with varying conditions of viewpoint, sound, visual background, and task difficulty. In Ma and Kaber's experiment, participants performed a basketball free throw task, and presence was related to attention results obtained from a secondary monitoring task. The results suggested that immersion (viewpoint) and auditory cues significantly influenced presence.

Although significant efforts have been devoted to classifying and proposing taxonomies for interaction metaphors (Bowman, Kruijff, LaViola, & Poupyrev, 2004), more research is needed in order to understand their role in eliciting presence. Usually, the virtual hand metaphor is considered to be the most natural, but more empirical study is needed to confirm this hypothesis.

1.1.3 Presence Measurement. The most common instruments for measuring presence are subjective questionnaires. Some of them are widely accepted (Witmer & Singer, 1998; Slater, Steed, McCarthy, & Maringelli, 1998) and are also used in this study. However, an objective measurement of presence within a VE would represent a powerful tool to obtain quantitative measurements that can overcome subjectivity, which can be considered a primary drawback of presence questionnaires (Bailenson et al., 2005; Slater, 2004). For a review of presence measurement methods, see IJsselsteijn, de Ridder, Freeman, and Avons (2000).

One possible approach to these objective measurements is based on spontaneous behavioral responses that people normally exhibit in the real world when particular stimuli are present. Some movements, such as those made to reach a virtual object or to wave to virtual avatars, might suggest that participants actually believe that they are within the VE. Hence, postural movements seem to be an interesting indicator of presence, as reported by other authors (Cohn, DiZio, & Lackner, 2000; Held & Durlach, 1993; Prothero, Parker, Furness, & Wells, 1995; Sheridan, 1992; Slater, Usoh, & Steed, 1995).

Nichols, Haldane, and Wilson (2000) visually classified participants' reactions to a startling event and found that the results of this measurement correlated positively with the reported sense of presence. Sheridan (1992) proposed reflex responses, such as catching a ball or avoiding an object thrown toward the subject, as a measurement of presence.

Attention has been also paid to analyze together both types of measurements, questionnaires and postural movements. Slater, Usoh, and Chrysanthou (1995) measured participants' responses to virtual stimuli when incoherent real stimuli were also provided. In particular, they measured participants' actions of pointing to a virtual model of a radio, when the audio stimuli associated with the radio came from a different position. Slater, Usoh, and Steed (1995) also compared the behavior and presence rates obtained through a questionnaire of an experimental group and a control group in a visual cliff scenario. The results of both studies showed that the sense of presence was significantly related to the movements made to signal the virtual radio and the path walked by participants.

Nevertheless, measurements based on postural responses have also been proven to be not valid and reliable enough to be considered as a unique estimator of presence. Freeman, Avons, Meddis, Pearson, and IJsselsteijn (2000) reported that postural responses to motion stimuli and presence rates were not related, and they pointed out the need for further analysis of postural measurements. Following this approach, Bailenson et al. (Bailenson, Blascovich, Beall, & Loomis, 2001; Bailenson et al., 2008) have investigated aspects associated with postural movements, such as personal space limits, viewpoint, distance, and angle, in relation with the social presence of a virtual person or avatar.

Here, presence measurement is mainly based on questionnaires, but we also present a novel approach based on measuring involuntary movements in order to advance the knowledge needed in order for objective measurements to become a valid and reliable option.

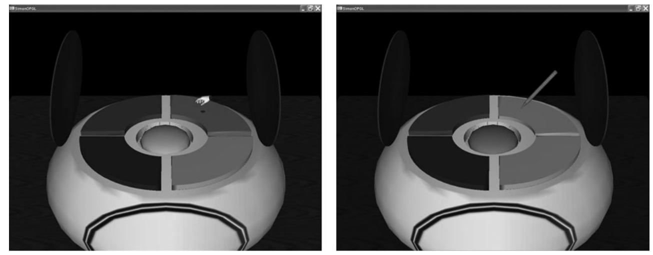
1.2 Study Rationale

A great deal of research has been conducted on the role of haptics in task performance and presence while interacting within a VE. Some of these studies have used a virtual hand metaphor, while others have used a virtual stylus metaphor in the context of a selection task. Usually, researchers suggest heuristically that direct selection using the participant's hand with haptic feedback makes interaction more efficient and improves the experience. However, it is important to comparatively assess how the chosen metaphor can influence both task performance and presence. The main goal of this study is to contribute to this assessment as well as to examine the possible interaction between the metaphor and the inclusion of haptic feedback. Therefore, our main hypothesis is that presence and task performance will be improved by haptic feedback and direct selection. Furthermore, while we have no prediction concerning the interaction, we perform an exploratory analysis. Finally, we also introduce a new objective presence measurement based on haptic movements.

2 Method

2.1 Participants

Twenty-four participants (20 men, four women) were recruited from the Telecommunications Engineering School at the University of Málaga. Participants were aged between 24 and 38 (M = 28.6; SD = 3.2). No compensation or reward was offered for their participation. All participants were quite experienced with computers, using them every day. Nevertheless, they were all novice users of VR applications, as none of them had used VR devices before.



(a) (b)

Figure 1. *Simon device as used by the participants under both the hand and tool conditions (interaction metaphor factor).*

2.2 Apparatus

The experimental setup reproduced a virtual version of the popular game Simon (see Figure 1). This game is a simple device that consists of four differently colored buttons. The system shows a random sequence (by lighting the buttons and emitting a different sound for each button) and the user must then try to reproduce the sequence correctly by pushing the buttons. The classic Simon game gradually increases the length of the sequences shown. However, our setup was designed with two fixed sequence lengths in order to control this variable better: four steps (low level of difficulty) and six steps (high level of difficulty). When the sequence was not correctly reproduced by the participant, an error sound was emitted and, sometimes (one in every four occasions), two virtual lateral plates (see Figure 1) were suddenly closed, emitting a clashing sound and catching the user's virtual hand between them. This mechanism was implemented in order to elicit an involuntary self-protection response that may be recorded and used as an estimator of presence.

The participants either interacted with the virtual Simon game by directly using their hand or by using a wooden stylus (interaction metaphor factor). Depending on the technique used, the virtual representation within the VE consisted of a small 3D icon representing a hand (as shown in Figure 1[a]) or a virtual stylus (as shown in Figure 1[b]). A magnetic tracker (Flock of Birds by Ascension) was used to track the position of the user's fingers or the stylus back end. This tracker

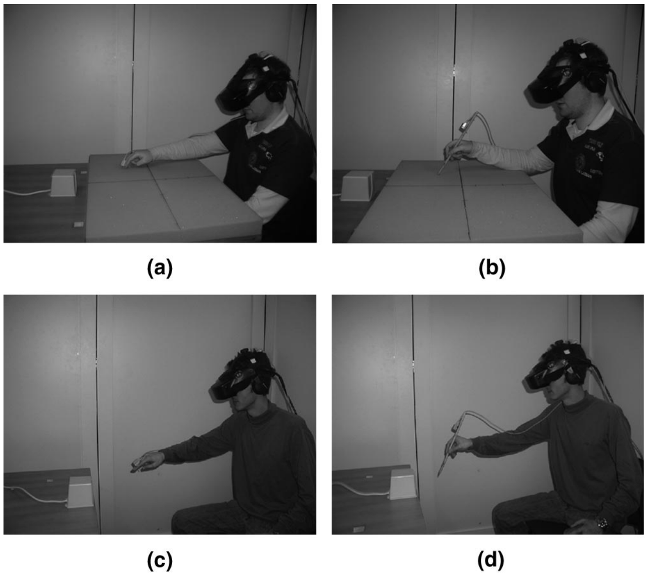


Figure 2. *Participants in the HF and NHF groups interacted in two blocks: (a) HF-hand, (b) HF-tool, (c) NHF-hand, (d) NHF-tool.*

was placed in the second phalange of the index, middle, and ring fingers or at the back end of the stylus, as can be seen in Figure 2. When interacting using their hands, participants were told to keep their fingers together. The system implemented passive force feedback via a real surface placed under the participant's hand (see Figure 2). This surface was covered with soft foam rubber. The foam rubber was used to avoid slight mismatches between the virtual surface and actual positions of the prop, as well as to achieve a more realistic feeling when pushing a button that is supposed to move downward slightly in that situation (Viciana-Abad, Reyes-Lecuona, & Cañadas-Quesada, 2005).

The system shows when a button is selected by illuminating it, moving it down and emitting a typical beep that lasts 200 ms, of a different frequency for each button. As an accuracy constraint, if the user pushes the button more than 2.4 cm deep, the button is released. In addition, in order to provide additional visual cues when a button is pressed, we implemented a pseudo-haptic mechanism, similar to other optically simulated haptic feedback (Mensvoort, Hermes, & Montfort, 2008). The implemented technique slows down the hand or stylus movement by a scale factor of 0.4 when the button is touched, simulating the resistance of a real button.

We provided stereoscopic visualization with a head mounted display (V8 by Virtual Research), displaying a 35-cm diameter Simon about 60 cm distant from the user's viewpoint. Our apparatus featured headphones to provide audio feedback. We used a second magnetic tracker to track head movements and to set the virtual viewpoint.

2.3 Procedure

We divided the participants randomly into two groups of 12. As shown in Figure 2, one group interacted with the system in a haptic feedback situation (group HF), while the other group interacted in a non-haptic feedback scenario (group NHF). Each group interacted with the system in two blocks, differentiated by the interaction metaphor. In one of the blocks, they interacted directly with their hand (hand condition), and in the other, they used the stylus (tool condition). The block order was counterbalanced in order to eliminate learning effects. Half of the participants interacted first in the hand condition and the other half started in the tool condition.

Furthermore, in order to ensure that the sequence length was neither too short nor too long, two different sequence lengths were used: short sequences (four steps) or long sequences (six steps). Hence, the sequence length was a within-subject and within-block factor. For every block, participants had to reproduce 34 sequences. The first four sequences were considered for adaptation and results were not recorded. Thereafter, 15 long sequences and 15 short sequences were presented in a random order.

Therefore, this experiment had a $2 \times 2 \times 2$ design with three independent variables, which are referred to throughout this paper as haptic feedback factor, interaction metaphor factor, and sequence length factor. The dependent variables are sense of presence and task performance. Figure 3 summarizes the experimental design.

The experiment took place in a research laboratory. Upon arrival, participants completed consent forms. We

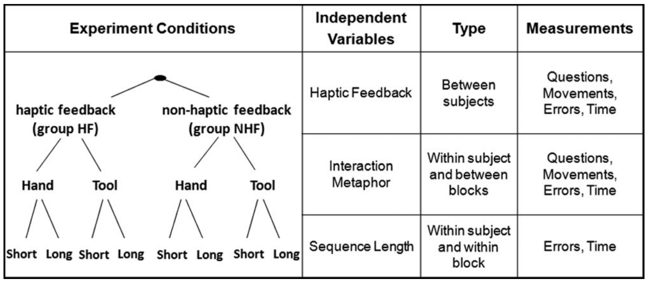


Figure 3. *Experiment design: independent variables and measurements.*

administered the ITQ (immersion tendency questionnaire; Witmer & Singer, 1998), although we did not ultimately use the results. Then, they were informed about their participation as subjects of an experiment within a VR environment that features the Simon game. The selection constraints of the task were explained, emphasizing that pressing a button too hard would result in its being released. Instructions on how to play were also given in case anyone did not know the game. They were told that the main goal was to correctly reproduce the maximum number of sequences. The speed at which they reproduced the sequence was considered a secondary goal.

2.4 Measurements

After every block, participants were asked to complete the presence questionnaire (PQ). PQ components were taken from two different factorizations of the PQ questionnaire: control/involvement (C/I), naturalness (NAT), interface quality (IQ), auditory (AU), haptic (HAP), and resolution (RES) (Witmer & Singer, 1998); and involvement (INV), sensory fidelity (SF), and adaptation/immersion (AI) (Witmer, Jerome, & Singer, 2005). The overall presence score (PRE) was computed from the average answers to all the items included in both factorizations. The PQ was translated into Spanish because this was the native language of all the participants.

In addition, the Slater-Usoh-Steed questionnaire (SUS), for measuring presence (Slater et al., 1998), was also administered (again translated into Spanish). The SUS was evaluated by computing the number of answers rated over 5 (as proposed by the author). Thus, as this questionnaire features five items, the results ranged from 0 (no answer above 5) to 5 (all answers above 5).

We also evaluated the sense of presence using objective measurements related to involuntary hand movements made by participants as a consequence of the virtual clashing plates, described above. One in every four errors triggered the clashing plates event. Thereafter, the hand or stylus position was recorded over the subsequent 2 s. The recorded position corresponds to the position of the motion tracker. Trajectories depicted by the hand or pointer as a response to this virtually dangerous event were expected to be related to different levels of presence. In the case of errors in which the event was not triggered, the movement recorded was considered a control condition.

With these data, a 3D graph was plotted to represent the average trajectory of the hand or stylus for each condition. In order to compute this average, the tracker was considered to be at the origin (0, 0, 0) at the beginning of each recording period. Then, the average position for each time t thereafter was computed as follows:

$$[\bar{X}(t), \bar{Y}(t), \bar{Z}(t)] = \left(\frac{\sum_{i=1}^{N} x_i(t)}{N}, \frac{\sum_{i=1}^{N} y_i(t)}{N}, \frac{\sum_{i=1}^{N} z_i(t)}{N} \right)$$

where $x_i(t)$, $y_i(t)$, and $z(t)$ are the x, y, and z coordinates, respectively, of the hand or pointer at time t after the ith error. N is the total number of samples to be averaged.

As measurements of task performance, the number of errors (referred to from now on as Errors) and the average time elapsed between button pressings (referred to from now on as Time) were recorded.

3 Results

As the interaction metaphor factor was a within-subject variable, half of the participants interacted with their hands first and the other half interacted using the

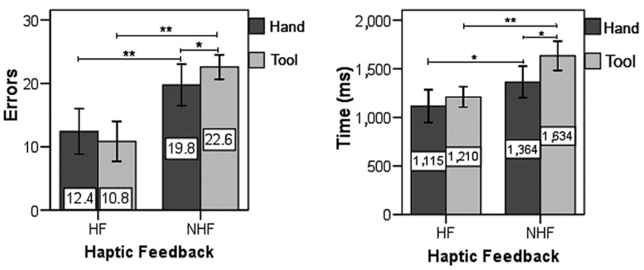


Figure 4. *Mean results (*p < .05, **p < .001) in task performance for the four experimental conditions: HF-hand, HF-tool, NHF-hand, and NHF-tool.*

stylus first. In order to discard any possible learning effects, we performed a three-factor ANOVA with the order (hand-first or stylus-first) as a between-subjects factor, together with haptic feedback (between-subjects factor) and interaction metaphor (within-subject factor). No significant main effect of the order was found in any of the dependent variables and, most importantly, no significant interaction for either interaction metaphor or haptic feedback was found with order. Therefore, we discarded any possible effects of order.

3.1 Task Performance

We calculated a three-factor ANOVA with haptic feedback as a between-subjects variable, interaction metaphor as a within-subject variable, and sequence length as a within-subject variable. There were main effects of presence of haptic feedback, Errors: $F(1, 22) = 31.88$, $p < .001$, η^2 [1] $= .59$; Time per response: $F(1, 22) = 16.31$, $p = .001$, $\eta^2 = .42$. As Figure 4 illustrates, both Time and Errors were significantly lower in group HF than in group NHF. The interaction metaphor factor also significantly influenced Time, $F(1, 22) = 9.45$, $p = .006$, $\eta^2 = .30$, but not Errors, $F(1, 22) = 0.43$, $p = .51$, $\eta^2 = .01$. Subjects selected buttons faster by hand than with the stylus, as illustrated in Figure 4.

We included the sequence length to ensure that sequence length was neither too long nor too short, obscuring the effect of haptic feedback or interaction metaphor. As expected, Errors were significantly fewer in short sequences than in long sequences, $F(1, 22) = 82.87$, $p < .001$, $\eta^2 = .79$, although Time per response was not influenced by the sequence length, $F(1, 22) = 2.25$, $p = .14$, $\eta^2 = .09$. Nevertheless, we identified no significant interaction between the sequence length factor and the other two factors. Therefore, we did not analyze sequence length further.

We also found a significant interaction between the interaction metaphor and haptic feedback factors in terms of task performance, Errors: $F(1, 22) = 4.93$, $p = .04$, $\eta^2 = .18$; Time: $F(1, 22) = 5.18$, $p = .03$, $\eta^2 = .19$. Therefore, we also performed Student *t* analyses, considering separately the results for both haptic groups and both metaphor conditions (see Table 1 and Figure 4). This analysis showed that for the haptic feedback group, there were no significant differences between the tool and the hand group. For the nonhaptic feedback group, both performance measurements were lower in the hand condition than in the tool condition, Errors: $t(11) = -2.05$, difference $= -2.83$, $p = .05$; Time: $t(11) = -2.99$, difference $= -270$ ms, $p = .01$.

3.2 Presence

We performed a two-factor ANOVA with haptic feedback as the between-subjects variable and interaction metaphor as the within-subject variable. We used scores from both the PQ and SUS questionnaires as dependent variables. As listed in Table 2, significant influences were only found for the haptic feedback factor in the NAT, $F(1, 22) = 6.47$, $p = .01$, $\eta^2 = .22$, and INV, $F(1, 22) = 5.35$, $p = .03$, $\eta^2 = .17$, components of PQ. The haptic component (HAP) was not significantly influenced by haptic feedback. Although this may seem surprising, one potential (though ad hoc and preliminary) explanation is that the items in PQ that are related to this component (*How well could you actively survey or search the virtual environment using touch?* and *How well could you move or manipulate objects in the virtual environment?*) were not appropriate for the simple selection task chosen in this study.

Neither of the two subjective measurements used (PQ and SUS questionnaires) were able to highlight any

1. Partial eta-squared measure.

Table 1. *Task Performance Results*,***

Measurements		Hand block†	Tool block†	Group HF‡	Group NHF‡
Errors	Difference	−7.33	−11.75	1.58	−2.83
	p	**.003**	**.001**	.30	**.05**
Time (ms)	Difference	−248	−424	−94	−270
	p	**.03**	**.001**	.18	**.01**

*Differences between haptic feedback conditions for each interaction metaphor condition; and differences between interaction metaphor conditions for each haptic feedback group.
**Rows show differences between conditions and their significant values taken from Student t analyses. Mean values for every condition are shown in Figure 4.
†Differences between haptic feedback conditions are calculated as HF-NHF (between subjects, $n = 12$).
‡Differences between interaction metaphor conditions are calculated as hand tool (within subject, $n = 12$).

Table 2. *Overall Presence Factors and PQ Components: Influence of Interaction Metaphor and Haptic Feedback Factors and Interactions*

		PRE	SUS	C/I	NAT	IQ	AUD	HAP	RES	INV	SF	AI
Haptic feedback	$F(1, 22)$	2.93	.32	3.50	6.47	0.66	0.01	3.31	0.07	5.35	0.05	3.76
	p	.10	.54	.08	**.01**	.53	.89	.08	.78	**.03**	.81	0.06
	η^2	.11	.01	.13	.22	.01	.01	.13	.004	.17	.002	.14
Interaction metaphor	$F(1, 22)$	1.15	.09	1.19	0.12	0.08	2.37	0.74	2.98	0.27	2.83	0.06
	p	.29	.76	.28	.73	.77	.13	.39	.09	.60	0.10	.80
	η^2	.05	.004	.05	.005	.004	.09	.03	.11	.01	.11	.003
Haptic feedback metaphor	$F(1, 22)$	1.87	2.31	2.47	.21	1.01	0.04	0.74	0.86	1.41	0.01	0.84
	p	.18	.14	.13	.64	.32	.82	.39	.36	.24	.92	.36
	η^2	.07	.09	.10	.01	.04	.002	.03	.03	.06	.001	.03

significant differences in presence as an overall factor. However, some of the PQ components were influenced by the study conditions. This may be due to the different nature of the two questionnaires. While the PQ questionnaire is based on an analysis of those factors that may enhance presence, the Slater questionnaire is based on the definition and consequences of presence. Therefore, the results of the Slater questionnaire relied more on the participants' conception of presence, for which reason it was more difficult to establish clear differences between the conditions.

Figure 5 illustrates in more detail the results obtained for all the conditions and all the factors of relevance to the PQ survey. We also analyzed the simple effects of haptic feedback and interaction metaphor for the overall scores on both PQ and SUS questionnaires. This analysis is listed in Table 3. In spite of not identifying significant interactions between the factors considered, we performed this analysis to determine the extent to which our presence results matched the findings obtained under our task performance measurements. Considering hand and tool conditions separately, we note that haptic feedback significantly increased presence scores (PRE factor) when using a stylus. This was not the case when using the hand. Furthermore, if we consider the haptic feedback and nonhaptic feedback groups separately, in-

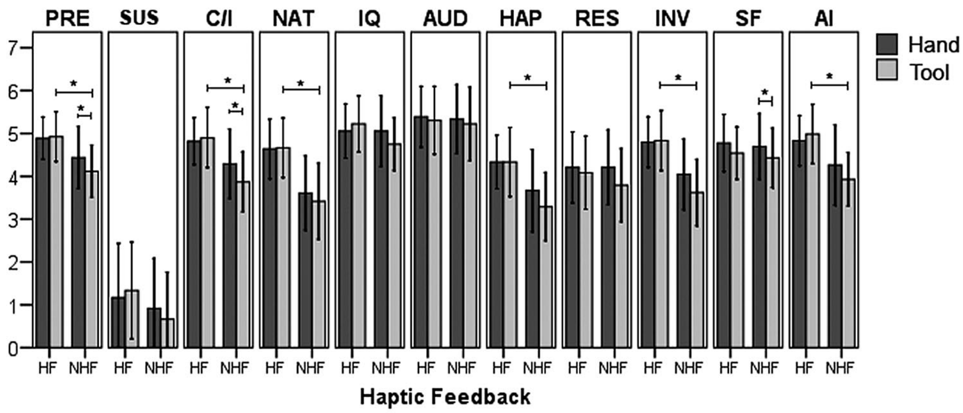


Figure 5. *Mean results (*p < .05) in the context of overall presence factors (PRE, SUS) and PQ components for the four experimental conditions: HF-hand, HF-tool, NHF-hand, and NHF-tool.*

Table 3. *Overall Presence Factors; Differences Between Haptic Feedback Conditions for Each Interaction Metaphor Condition; and Differences Between Interaction Metaphor Conditions for Each Haptic Feedback Group**

Measurements		Hand block**	Tool block**	Group HF†	Group NHF†
PRE	Difference	0.45	0.80	−0.03	0.31
	p	.26	**.04**	.87	**.04**
SUS	Difference	0.25	0.66	−0.16	0.25
	p	.75	.36	.43	.19

*Rows show differences between conditions and their significant values taken from Student *t* analyses. Mean values for every condition are shown in Figure 5.
**Differences between haptic feedback conditions are calculated as HF-NHF (between subjects, $n = 12$).
†Differences between interaction metaphor conditions are calculated as hand-tool (within subject, $n = 12$).

teracting directly with one's hand significantly increased presence only when haptic feedback was not provided. This was not the case when haptic feedback was present.

To summarize, the condition that combines a stylus with no haptic feedback was significantly worse than any of the other three in terms of subjective presence ratings.

3.2.1 Measurements Based on Movements.

This novel measure of response is largely exploratory, and we rely on descriptive analyses of these data. Since the motion tracker was attached to the fingers in the hand conditions and to the back end of the stylus in the tool conditions, our recorded measurements were not comparable for these cases. Therefore, we analyzed both interaction metaphors separately.

Figure 6 shows the average trajectories of the user's hand in the 2 s following each error, while Figure 7 shows the corresponding stylus trajectories. Three dimensional plots are shown (Figures 7[a] and 7[b]), together with the lateral projections (Figures 7[c] and 7[d]) and horizontal projections (Figures 7[e] and 7[f]), for groups HF and NHF. Figures 7(a, c, and e) show the control situation (no clashing plates) and Figures 7(b, d, and f) show the situation where the virtual clashing plates are closed. In these graphs, trajectories begin at (0, 0, 0) at the moment that an incorrect button was pressed. The arrow labeled "subject" represents the approximate location and direction of the user's viewpoint.

As shown in Figure 6, when participants interacted directly with their hands, movements in both the con-

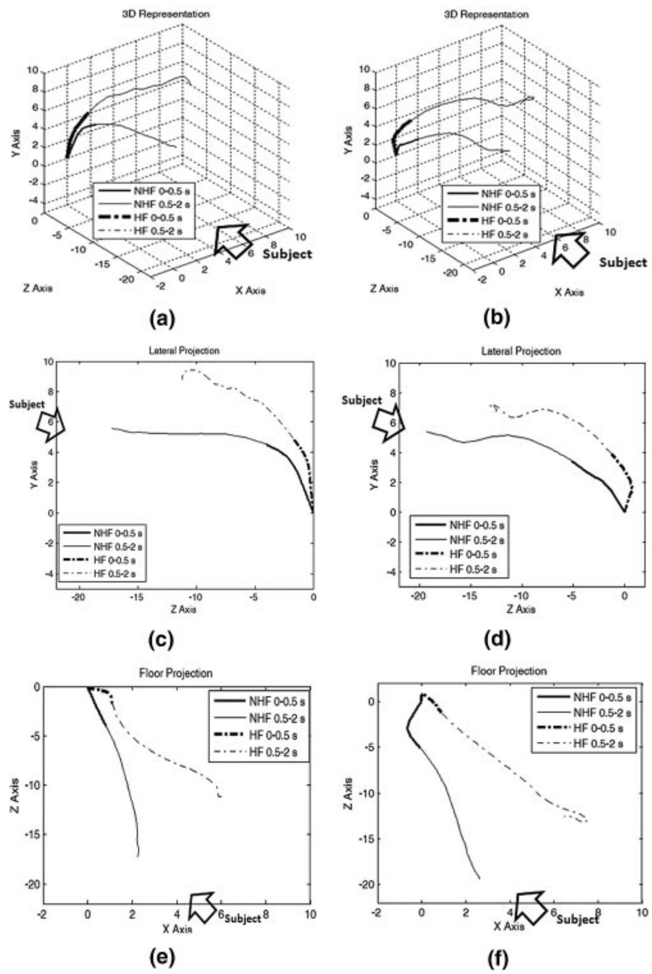


Figure 6. *Average trajectories of the users' hands, in the control and the clashing plates scenarios, under the hand condition, for HF and NHF groups: in 3D (a, b); and their projections in the lateral plane (c, d) and in the horizontal plane (e, f).*

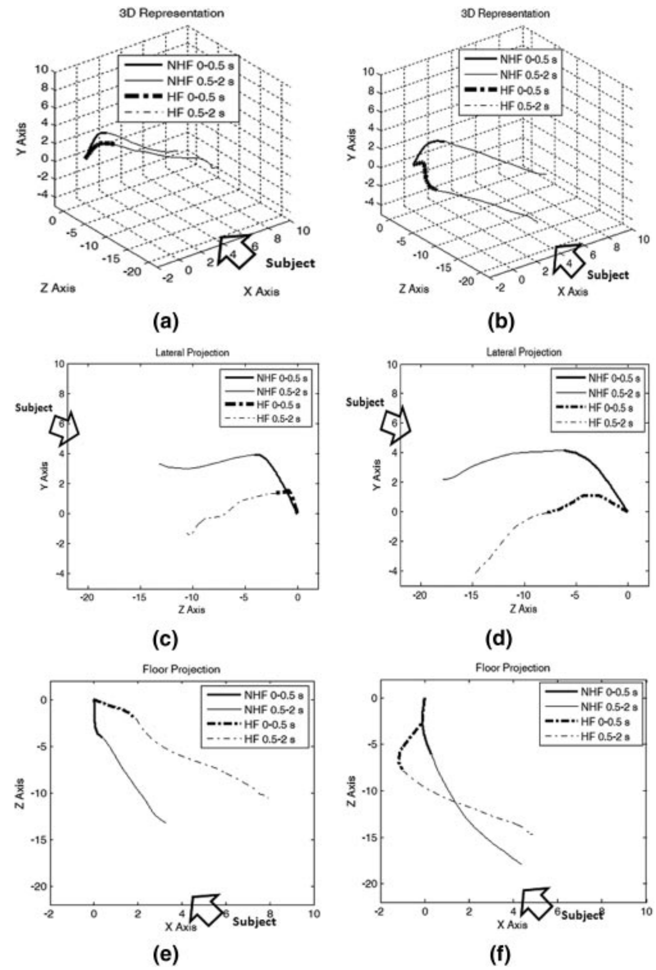


Figure 7. *Average trajectories of the users' hands, in the control and the clashing plates situations, during the tool condition, for HF and NHF groups: in 3D (a, b); and their projections in the lateral plane (c, d) and the horizontal plane (e, f).*

trol and the clashing plate situations were very similar for groups HF and NHF. However, when using the stylus (see Figure 7), the differences between the control and clashing plates situations were clearly more pronounced for group HF than for group NHF. This is especially noticeable in the horizontal projections (Figures 7[e] and 7[f]). Therefore, the most evident differences between HF and NHF conditions were produced when interacting with the stylus. This was consistent with results regarding the reported level of presence, as presented above.

We performed a linear regression between subjective presence rates reported via the PQ questionnaire, as the dependent variable, and participants' displacement along the three axes 2 s after an incorrect button had been pressed, as the independent variable. Table 4 shows the linear regression characterization when selection was performed directly with the hand (hand condition). In this case, the level of presence was significantly correlated with the movements made. In the control situation, subjective rates were mainly related to displacement toward the participant's body (*z* axis). In the

Table 4. *Linear Regressions for Presence Score (PE) as the Dependent Variable and Hand Displacement in the x, y, and z Axes*

	R^2 (Determination coefficient)	p	Linear regression	Beta significance		
				β_x	β_y	β_z
Control	.40	***.01***	$P = 0.28x + 0.37y + 0.47z + 4.60$	*.16*	*.07*	***.02***
Event	.34	***.03***	$P = 0.24x + 0.54y + 0.41z + 4.46$	*.20*	***.01***	***.04***

event situation, movement in the vertical direction (y axis) became more relevant.

On the other hand, we found no significant relationship between reported presence and stylus displacement 2 s after the error was made.

4 Discussion

The results presented above confirm our main hypothesis. Providing haptic feedback during a simple selection task enhances interaction by increasing both the sense of presence and the task performance. This result is a step forward to studies within the context of targeting selection where this positive influence was only assessed regarding performance metrics (Lindeman et al., 1999; Borst & Volz, 2003).

In addition, direct selection with the hand yields higher degrees of presence and task performance than using a stylus as a tool. Moreover, these two factors present similar interaction rates for both task performance and presence. Using a stylus without haptic feedback is clearly the worst situation. It is interesting to note that while interaction is significantly enhanced by haptic feedback and by direct selection, combining these factors does not further enhance interaction.

The positive influence of haptic feedback on the elicited sense of presence and the resulting task performance has been reported by other authors in several contexts, as described in Section 1. Most researchers used the classical virtual hand as an interaction metaphor. Our results confirm these findings and also reveal that this phenomenon is even more powerful when using a mediating tool to perform the selection task. Sallnäs et al. (2000) found similar results using a tool for collaboratively manipulating virtual objects, although they too identified an important effect in the context of social presence. Our results confirm their findings for a simple selection task where social effects are not present.

Interaction within a virtual environment is commonly achieved through devices such as remote controls, styluses, or joysticks, rather than by directly sensing the participants' hands via sensors or gloves. During participant interaction within a 3D environment, proprioceptive and tactile cues may impact the accuracy of selection tasks. Therefore, we have evaluated interaction differences when proprioceptive and tactile cues are perceived by participants directly through their hands, and when they are perceived through the stylus used. We assessed two interaction metaphors: the classical virtual hand metaphor, and also selection using a stylus. These two metaphors cover a wide range of practical applications in VR. However, there is little empirical evidence in the literature about the influence of these interaction metaphors on presence and task performance for simple selection tasks. Our results show that interacting directly with the hand results in more presence and better task performance, especially when no haptic feedback is provided.

Moreover, a clear interaction between these two factors has been identified. Interacting directly using the hand yields better presence and task performance than interacting with a stylus only when no haptic feedback is provided. If haptic feedback is provided, we found no significant difference between using the hand or a stylus to make selections. This is particularly relevant when we consider that tactile feedback was involved when participants depressed the foam surface with their fingertips.

This finding is especially important when designing 3D interfaces for haptic VR applications. Force feedback devices based on the stylus metaphor are a good solution, at least when the interaction consists of a simple selection task.

The current study has provided empirical evidence about the importance of considering the interaction metaphor as a factor that may determine the elicited sense of presence. This factor is mainly explored when an improvement in task performance is the main issue being considered within the simulation, but it has been less evaluated regarding the sense of presence. Certain aspects, such as the realism of the avatar used to represent the participant, have already been considered, but further research is required to assess the extent to which the tools and devices used to implement a specific interaction metaphor may influence the phenomenon of presence.

Many researchers have followed the approach of measuring presence with not only subjective reports but also measuring behavior. The studies have attempted to measure behaviors such as reactions with an avatar (Bailenson et al., 2001; Bailenson et al., 2008), in order to measure social presence; movements to avoid a danger such as a virtual cliff (Slater, Usoh, & Steed, 1995); or induced movements or vection (Cohn et al., 2000) as a consequence of virtual scenes in movement. Following the approach of objectively estimating presence, we propose a procedure based on measuring reactions to events originated within the VE. Therefore, we have been able to study whether such reactions change among different conditions and the extent to which they are similar to those expected in a real situation. We found that participants' response to an event within the VE was a more promising tool for highlighting possible differences in presence rates than absolute presence rates. Thus, this study is in accordance with those that have stated the need of carrying both measurements based on questionnaire and behavior. We also concluded that participants' movements may be correlated with subjective presence when these movements are directly measured in the participants' hands, but not so in the stylus. It is possible that movements measured indirectly (the back end of the stylus) may hide relevant details.

Although more research is needed about the use of this technique to analyze differences in presence according to conditions, this work is a step forward. We build on the study of Nichols et al. (2000), in which participants' responses were tracked only visually. We conclude that the use of behavior as an indicator of presence may be challenging due to its difficulty of being interpreted as a direct measure of presence. Many uncontrollable factors may influence this measurement, such as the position used to track this behavior. In the case of tracking the position of the user's hand, we identified a relationship between hand movement and subjective presence. A similar relationship was previously found by Slater et al. (1998) in a study where they measured the participants' head and arm movements in order to clearly identify trees within a VE.

In sum, our paper yields more precise insights about which conditions of interaction are more likely to positively influence presence and task performance while performing selection tasks within a virtual environment. We have considered two main factors for a selection task, the haptic feedback provided and the metaphor implemented, analyzing not only their contribution but also possible cross-interactions. Thus, one of the main conclusions raised is that, when no haptic feedback is provided, the complexity beneath the metaphor chosen must be considered. Nevertheless, when haptic feedback is provided, the metaphor used is not so determinant in the sensorimotor interaction model used to evaluate the transparency of the technology that mediated the experience within the virtual environment.

An objective technique based on the users' reaction when an event takes place has also been tested as a measurement of presence. The study carried out has indicated that this behavior may be used together with subjective reports to highlight those conditions with significant difference in the elicited sense of presence. Nevertheless, further research is needed to characterize this behavior in such a way that can be interpreted as a direct measurement of presence.

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References

Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2001). Equilibrium theory revisited: Mutual gaze and personal space in virtual environments. *Presence: Teleoperators and Virtual Environments, 10*(6), 583–598.

Bailenson, J. N., Davies, A., Blascovich, J., Beall, A. C., McCall, C., & Guadagno, R. E. (2008). The effects of witness viewpoint distance, angle, and choice on eyewitness accuracy in police lineups conducted in immersive virtual environments. *Presence: Teleoperators and Virtual Environments, 17*(3), 242–255.

Bailenson, J. N., Swinth, K. R., Hoyt, C. L., Persky, S., Dimov, A., & Blascovich, J. (2005). The independent and interactive effects of embodied agent appearance and behavior on self-report, cognitive, and behavioral markers of copresence in immersive virtual environments. *Presence: Teleoperators and Virtual Environments, 14*(4), 379–393.

Bailey, J., & Witmer, B. (1994). Learning and transfer of spatial knowledge in a virtual environment. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting,* 1158–1162.

Biocca, F., Inoue, Y., Lee, A., Polinsky, H., & Tang, A. (2002). Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence. *Proceedings of Presence,* 410–428.

Bormann, K. (2006). Subjective performance. *Virtual Reality, 9*(4), 226–233.

Borst, C. W., & Volz, R. A. (2003). Observations on and modifications to the Rutgers Master to support a mixture of passive haptics and active force feedback. *Proceedings of 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS 2003,* 430–437.

Borst, C. W., & Volz, R. A. (2005). Evaluation of a haptic mixed reality system for interactions with a virtual control panel. *Presence: Teleoperators and Virtual Environments, 14*(6), 677–696.

Bowman, D. A., & Hodges, L. F. (1997). An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. *Proceedings of Symposium on Interactive 3D Graphics,* 35–38.

Bowman, D. A., Johnson, D. B., & Hodges, L. F. (2001). Testbed evaluation of virtual environment interaction techniques. *Presence: Teleoperators and Virtual Environments, 10*(1), 75–95.

Bowman, D. A., Kruijff, E., LaViola, J., & Poupyrev, I. (2004). *3D user interfaces: Theory and practice*. Reading, MA: Addison-Wesley.

Büscher, M., O'Brien, J., Rodden, T., & Trevor, J. (2001). "He's behind you": The experience of presence in shared virtual environments. *Collaborative Virtual Environments: Digital Places and Spaces for Interaction,* 77–98.

Cohn, J. V., DiZio, P., & Lackner, J. R. (2000). Reaching during virtual rotation: Context specific compensations for expected Coriolis forces. *Journal of Neurophysiology, 83*(6), 3230–3240.

Ellis, S. R. (1996). Presence of mind: A reaction to Thomas Sheridan's "Further musings on the psychophysics of presence." *Presence: Teleoperators and Virtual Environments, 5*(2), 247–259.

Ellis, S., Dorighi, N., Menges, B., Adelstein, B., & Jacoby, R. (1997). In search of equivalence classes in subjective scales of reality. In M. J. Smith, G. Salvendy, & R. J. Koubek (Eds.), *Design of Computing Systems: Social and Ergonomic Considerations. Proceedings of the Seventh International Conference on Human-Computer Interaction* (Vol. 2, pp. 873–876). Amsterdam: Elsevier.

Flach, J. M., & Holden, J. G. (1998). The reality of experience: Gibson's way. *Presence: Teleoperators and Virtual Environments, 7*(1), 90–95.

Freeman, J., Avons, S. E., Meddis, R., Pearson, D. E., & IJsselsteijn, W. (2000). Using behavioral realism to estimate presence: A study of the utility of postural responses to motion stimuli. *Presence: Teleoperators and Virtual Environments, 9*(2), 149–164.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Hecht, D., Reiner, M., & Halevy, G. (2006). Multimodal virtual environments: Response times, attention, and presence. *Presence: Teleoperators and Virtual Environments, 15*(5), 515–521.

Held, R., & Durlach, N. (1993). Telepresence, time delay and adaptation. In S. R. Ellis, M. K. Kaiser, & A. C. Grunwald (Eds.), *Pictorial communication in virtual and real environments* (pp. 232–246). London: Taylor and Francis.

Hendrix, C., & Barfield, W. (1996a). Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperators and Virtual Environments, 5*(3), 274–289.

Hendrix, C., & Barfield, W. (1996b). The sense of presence within auditory virtual environments. *Presence: Teleoperators and Virtual Environments, 5*(3), 290–301.

Hinckley, K., Pausch, R., Goble, J. C., & Kassell, N. F. (1994). Passive real-world interface props for neurosurgical visualization. *Proceedings of the CHI'94, Conference on Human Factors in Computing Systems* (pp. 452–458). New York: ACM.

Hoffman, H. G. (1998). Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. *Proceedings of the Virtual Reality Annual International Symposium'98,* 59–63.

IJsselsteijn, W. A. (2002). Elements of a multi-level theory of presence: Phenomenology, mental processing and neural correlates. *Proceedings of Presence,* 245–259.

IJsselsteijn, W. A., de Ridder, H., Freeman, J., & Avons, S. E. (2000). Presence: Concept, determinants and measurement. In B. E. Rogowitz & T. N. Pappas (Eds.), *Proceedings of SPIE* (Vol. 3959, pp. 520–529). Bellingham, WA: Society of Photo-Optical Instrumentation Engineers.

Insko, B. E. (2001). *Passive haptics significantly enhances virtual environments* (PhD Dissertation). Department of Computer Science, UNC Chapel Hill, North Carolina.

Liere, R. v., Martens, J., Kok, A., & Tienen, M. v. (2005). Interacting with molecular structures: User performance versus system complexity. *Proceedings of the Eurographics Symposium on Virtual Environments,* 147–156.

Lin, J. J. W., Duh, H. B. L., Abi-Rached, H., Parker, D. E., & Furness, T. A. (2002). Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. *Proceedings of IEEE Virtual Reality 2002,* 164–171.

Lindeman, R. W., Sibert, J. L., & Hahn, J. K. (1999). Handheld windows: Towards effective 2D interaction in immersive virtual environments. *Proceedings of the Virtual Reality Annual International Symposium,* 205–212.

Lok, B., Naik, S., Whitton, M., & Brooks, F. P., Jr. (2003). Incorporating dynamic real objects into immersive virtual environments. *Proceedings of ACM SIGGRAPH, 22*(3), 701.

Lombard, M., & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication, 3*(2), http://jcmc.indiana.edu/vol3/issue2/lombard.html.

Loomis, J. M. (1992). Distal attribution and presence. *Presence: Teleoperators and Virtual Environments, 1*(1), 113–119.

Ma, R., & Kaber, D. B. (2006). Presence, workload and performance effects of synthetic environment design factors. *International Journal of Human Computer Studies, 64*(6), 541–552.

MacLean, K. E. (2000). Designing with haptic feedback. *Proceedings of the IEEE International Conference on Robotics and Automation,* 483–788.

Maida, J., Aldridge, A., & Novak, J. (1997). Effects of lighting on human performance in training. In M. Smith, G. Salvendy, & R. Koubek (Eds.), *Design of computing systems: Social and ergonomic considerations* (pp. 877–880). Amsterdam: Elsevier Science Publishers.

Mania, K., Chalmers, A., Troscianko, T., & Hawkes, R. (2000). Presence and task performance: A reality centred approach. Technical sketch. *Proceedings of ACM SIGGRAPH 2000,* 245.

Meehan, M., Insko, B., Whitton, M., & Brooks, F. (2001). Physiological measures of presence in virtual environments. *Proceedings of the 4th Annual International Presence Workshop,* 21–23.

Mensvoort, K. v., Hermes, D. J., & Montfort, M. v. (2008). Usability of optically simulated haptic feedback. *International Journal of Human Computer Studies, 66*(6), 438–451.

Navarre, D., Palanque, P., Schyn, A., Winckler, M., Nedel, L., & Freitas, C. M. D. S. (2005). A formal description of multimodal interaction techniques for immersive virtual reality applications. *Proceedings of Interact,* 170–183.

Nichols, S., Haldane, C., & Wilson, J. R. (2000). Measurement of presence and its consequences in virtual environments. *International Journal of Human Computer Studies, 52*(3), 471–491.

Pausch, R., Proffitt, D., & Williams, G. (1997). Quantifying immersion in virtual reality. *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques,* 13–18.

Pierce, J. S., Stearns, B. C., & Pausch, R. (1999). Voodoo dolls: Seamless interaction at multiple scales in virtual environments. *Proceedings of the 1999 Symposium on Interactive 3D Graphics* (pp. 141–149). New York: ACM.

Popescu, G. V., Burdea, G. C., & Trefftz, H. (2002). Multimodal interaction modeling. In K. M. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications* (pp. 435–454). Mahwah, NJ: Lawrence Erlbaum.

Poupyrev, I., Billinghurst, M., Weghorst, S., & Ichikawa, T. (1996). The Go-Go interaction technique: Non-linear mapping for direct manipulation in VR. *Proceedings of ACM Symposium on User Interface Software and Technology,* 79–80.

Prothero, J. D., Parker, D. E., Furness, T. A., III, & Wells, M. J. (1995). Towards a robust, quantitative measure for presence. *Proceedings of the Conference on Experimental Analysis and Measurement of Situation Awareness,* 359–366.

Rosenberg, L., & Brave, S. (1996). Using force feedback to enhance human performance in graphical user interfaces. *Proceedings of CHI'96: Conference on Human Factors in Computing Systems,* 291–292.

Sallnäs, E. L., Rassmus-Gröhn, K., & Sjöström, C. (2000). Supporting presence in collaborative environments by haptic force feedback. *ACM Transactions on Computer-Human Interaction (TOCHI), 7*(4), 461–476.

Schubert, T., Friedmann, F., & Regenbrecht, H. (1999). Decomposing the sense of presence: Factor analytic insights. *2nd International Workshop on Presence,* 6–7.

Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments, 1*(1), 120–126.

Singer, M. J., Allen, R. C., McDonald, D. P., & Gildea, J. P. (1997). *Terrain appreciation in virtual environments: Spatial knowledge acquisition* (Technical Report 1056). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Science.

Singer, M. J., Ehrlich, J., Cinq-Mars, S., & Papin, J. (1995). *Task performance in virtual environments: Stereoscopic vs. monoscopic displays and head-coupling* (Technical Report 1034). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Science.

Slater, M. (2004). How colorful was your day? Why questionnaires cannot assess presence in virtual environments. *Presence: Teleoperators and Virtual Environments, 13*(4), 484–493.

Slater, M., Steed, A., McCarthy, J., & Maringelli, F. (1998). The influence of body movement on subjective presence in virtual environments. *Human Factors, 40*(3), 469–478.

Slater, M., Usoh, M., & Chrysanthou, Y. (1995). The influence of dynamic shadows on presence in immersive virtual environments. In M. Göbel (Ed.), *Proceedings of Virtual Environments* (pp. 8–21). London: Springer-Verlag.

Slater, M., Usoh, M., & Steed, A. (1995). Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction, 2*(3), 201–219.

Viciana-Abad, R., Reyes-Lecuona, A., & Cañadas-Quesada, F. (2005). Difficulties using passive haptic augmentation in the interaction within a virtual environment. *Proceedings of Presence 2005,* 287–292.

Wall, S. A., Paynter, K., Shillito, A. M., Wright, M., & Scali, S. (2002). The effect of haptic feedback and stereo graphics in a 3D target acquisition task. *Proceedings of Eurohaptics,* 23–28.

Welch, R. B. (1999). How can we determine if the sense of presence affects task performance? *Presence: Teleoperators and Virtual Environments, 8*(5), 574–577.

Witmer, B. G., Jerome, C. J., & Singer, M. J. (2005). The factor structure of the presence questionnaire. *Presence: Teleoperators and Virtual Environments, 14*(3), 298–312.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments, 7*(3), 225–240.

Zahorik, P., & Jenison, R. L. (1998). Presence as being-in-the-world. *Presence: Teleoperators and Virtual Environments, 7*(1), 78–89.