The Effect of Haptic Prediction Accuracy on Presence

Dominik Gall* Marc Erich Latoschik†

Human-Computer Interaction
Julius-Maximilians-Universität Würzburg, Germany

ABSTRACT

This paper reports on the effect of visually-anchored prediction accuracy of haptic information on the perceived presence of virtual environments. We designed an experiment which explicitly prevented confounding factors potentially introduced by virtual body ownership and/or agency. The experimental design consisted of two main conditions defining congruent vs incongruent visual and haptic cues. Presence was measured during as well as after exposure. A distance estimation task solely based on motor action and the visually-anchored spatial model of the environment was executed to control for perceptual binding. 56 healthy volunteers were randomly assigned to one of two groups in a single-blind mixed-group design study. The study revealed increased presence for high prediction accuracy and decreased presence for low prediction accuracy, while perceptual binding still occurred. The observed effect sizes were in the medium range. The results indicate a significant correlation between prediction accuracy of haptic information and the perceived realness and presence of a virtual environment which gives rise to a discussion about models for the dissociative symptom derealisation.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI

1 INTRODUCTION

Virtual *presence* is one of the major qualities associated with many Virtual Reality (VR) systems. Presence conceptualizes the subjective sensation of being in a specific place or environment [48, 51]. The initial construct was criticized for being ambiguous and to capture different conceptualizations [48], which motivated a later differentiation into (1) *place illusion* and (2) *plausibility illusion* [55]. In this paper we refer to presence in the sense of place illusion, which is defined as "the strong illusion of being in a place in spite of the sure knowledge that you are not there" [55, p. 3551]. Breaks in presence denote violations of a successful place and plausibility illusion. They hinder a willing suspension of disbelief that users are located in a world other than where their real bodies. Breaks in presence can be caused by incoherent simulations and poor sensorimotor contingencies, for example, due to technical deficiencies of the mediating VR system. Sensorimotor contingencies, on the other hand, denote the modality-specific matching of sensory information to the "structure of the rules governing the sensory changes produced by various motor actions" [41, p. 941].

Potential correlations between presence and sensorimotor contingencies have been proposed. For instance, Seth [51] suggests a Bayesian model that defines presence as a function of the success of predicting sensory consequences of motor actions. In addition, Seth [51] argues for the clinical relevance of presence to understand dissociative disorders or prodromal schizophrenic symptoms. Hence, these conceptualizations emphasize the importance of expectations or predictions for the emergence of presence: presence is understood as a function of the match between visually induced expectations and actual sensory sensations. However, there is a lack of empirical research showing systematic influences of sensory prediction on presence, which is investigated here. Hence, the following hypothesis is guiding the main research goals of this work: Presence, i.e., the place illusion, is correlated to and determined in part by the accuracy of predicting sensory consequences of motor actions.

1.1 Contribution

We propose an immersive VR-based experimental design to investigate correlations between presence and sensorimotor contingencies. The design deliberately renounces inclusion of a virtual body. Our results reveal that presence is significantly correlated to the accuracy of predicting sensory consequences of motor actions while multisensory stimuli are successfully merged into a coherent percept. Hence, we could ensure the results to not be confounded neither (1) by the cognitive representation of distinct spatial reference systems nor (2) by virtual body ownership and agency.

2 RELATED WORK

2.1 Presence

Several definitions of presence have been proposed [31], many in line with a general conceptualization as to be a "perceptual illusion of non-mediation" [32]. VR users are embedded in a close human-computer interaction loop where they receive a continuous stream of computer-mediated sensory information. If the mediated stimuli match stimuli as expected from the real physical world, the mediated system is no longer perceived, suspension of disbelief occurs, and the artificial stimuli are accepted as being real for these users.

The refining notions of *spatial presence* [66] or place illusion [55] emphasize physical aspects of the perceptual illusion, operationalizing the sensation of one's self being physically situated within an environment. Different aspects of presence are discussed, for example in Lombard and Jones [33] or Laarni et al. [28]. The presence construct is not solely applicable to mediated experiences, links to psychological conditions related to the perception of the real world have been shown, supporting the validity of the construct [2, 38, 50].

The initial presence construct faced criticism due to a wide variety of definitions and attempts of operationalization [48] which motivated refinements: it was hypothesized that presence is primarily a function of the coherence of perceived responses of the mediated environment to the expectations induced by performed actions [42, 50, 56]. In this respect, Slater [55] refers to the concept of sensorimotor contingencies [40, 41], that describes the matching between expectancies in sensory changes due to motor action and reformulates theses aspects of presence as place illusion. This approach follows Gibson's affordance theory [16], in which a reciprocal relation between perception and action is assumed.

The perceived ability to executable actions in a virtual environment is suggested to be an additional moderator for presence [48]. This is supported by results showing activation of the primary and secondary motor cortex in response to immersive stimuli without resulting in overt actions [4, 37]. During temporally extended interaction with an environment, it can be assumed that the perceived ability to act is informed by experienced action effects since action

*e-mail: dominik.gall@uni-wuerzburg.de
†e-mail: marc.latoschik@uni-wuerzburg.de

2018 IEEE Conference on Virtual Reality and 3D User Interfaces
18-22 March, Reutlingen, Germany
978-1-5386-3365-6/18/$31.00 ©2018 IEEE
DOI: 10.1109/VR.2018.8446153

planning is guided by anticipated perceptual effects [24]. In turn, visual perception has been shown to be malleable in relation to perceived opportunities for action and the associated physical costs [43], further supporting an association of anticipated action and presence.

Figure 1: General overview of the experimental design. Top: The participant is seated in an office chair before a real physical table while wearing a head-mounted display. Bottom: In the virtual environment the physical table is substituted by a virtual replica of the real table. During the study, the spatial alignment between the real and the virtual table and hence the coherence between the real physical and the virtual world are modified.

2.2 Visuotactile and Visuomotor Stimulation

If presence is understood in terms of sensorimotor contingencies as a function of expectations and predictions about sensory information, by definition, the interaction of haptic and visual feedback is a significant determinant for the perception of presence. Haptic cues, in turn, can be divided into two categories: those arising from mechanoreceptors and thermoreceptors in the skin (cutaneous signals), and those resulting from mechanoreceptors in muscles, tendons, and joints (kinesthetic signals) [30]. This division emphasizes the difference between touching and being touched [15]. The activation of cutaneous signals by passive touch tends to lead the attention of the individual to its subjective bodily sensations, whereas the additional activation of kinesthetic cues by active exploration of with the limbs tends to direct the attention of the individual to the external environment [14, 15, 29, 30].

We refer to tactile feedback as "perception mediated solely by variations in cutaneous stimulation" [34, p. 31-2], and to haptic feedback, as a perception in which "both the cutaneous sense and kinesthesis convey significant information about distal objects and events" [34, p. 31-3]. The interaction of haptic feedback and perception of presence was subject to previous studies (discussed below), which directly or indirectly induce synchronous visuotactile and visuomotor stimulation of a real and virtual representation of the hand. However, such stimulations induce the illusion of virtual body ownership and agency [57, 69], which in turn was suggested to influence the sense of presence [58] and which, accordingly, have to be considered as confounding factors for investigating the effect of haptic prediction accuracy on presence.

2.3 Haptic Feedback and Presence

Dinh et al. [9] reported a significant increase of presence using combined cutaneous skin sensations of heat and wind in a visual environment. No active exploration occurred, so no kinesthetic signals and no haptic feedback was provided. Participants showed a significant increase in heart rate [35] in a virtual-height scenario, where they stood on a ledge in haptic correspondence to a virtual edge. In [19], participants picked up a virtual object that possessed haptic solidity and weight with a virtual representation of their hand. As a result, they predicted other objects in the virtual environment as to be more solid, heavier and more likely to obey gravity.

Hoffman et al. [18] showed an increased effectiveness of virtual reality exposure therapy (treatment of arachnophobia) and significantly higher presence in the case where the patient could control a virtual hand to explore the visual stimulus of a virtual spider accompanied by a physical toy spider. Kuschel et al. [27] observed a decrease in presence for increased incoherence when studying the effects of a dynamic visual and haptic deformation feedback task for objects. Here, an abstract representation of fingers was visually presented at the point of interaction thus inducing virtual body ownership and agency.

3 Experimental Design

When visual and haptic sensory cues are available simultaneously, information from the different sensory modalities are either dissociated or integrated such that a coherent multi-sensory percept is formed [11]. In case contradictory multi-sensory cues are perceptually bound to a single multi-sensory percept [45, 60], it has been suggested that discrepancies are resolved in favor of the modality that derives the more reliable or more appropriate estimate of for the given contradictory parameter [46, 52, 64]. Ernst and Banks [10] show that the integration of conflicting visual and haptic cues into one estimate can be modeled as an optimal Bayesian integration process. This model is supported by strong evidence, reviewed, for example, by Körding and Wolpert [26] and Fetsch et al. [12]. A failure of perceptual binding would lead to the cognitive representation of distinct objects challenging the sensation of a coherent virtual environment, hence confounding the sensation of presence.

To validate the assumption that perceived presence is a function of visually-anchored sensory expectations, and hence may vary according to the accuracy of predicting sensory consequences of motor actions, the degree of coherence between haptic feedback and visually-anchored haptic expectations has to be varied. For this task we designed a real/virtual environment with a modifiable visual-haptic coherence condition as depicted in Figure 1. Participants were placed in front of a real table while being immersed via an HMD in a virtual environment consisting of a simulated replica of the real office table. Participants were asked to haptically and visually explore the real/virtual table, where the visual exploration establishes the general spatial anchoring of sensory expectations. The spatial alignment between the real and the virtual table was modified to induce sensory mismatch as illustrated in Figure 3. In this design, no representations of body parts were presented in order to eliminate the potentially confounding effects of virtual body ownership and agency.

Assuming that the perception of presence is a function of perceived prediction accuracy, an increase of subjective presence ratings was expected for the spatial coincidence condition, and a decrease was expected for violated spatial coincidence, due to the reduction in prediction accuracy. Furthermore, we controlled if the contradicting bi-modal sensory information was integrated to a single coherent cognitive representation of the percept, since the absence of sensory integration (the cognitive representation of two distinct percepts), was expected to confound the sensation of presence. To rule-out a potential absence of sensory integration, we included an additional distance estimation task where the participants had to locate and press a virtual button appearing in the middle of the virtual table (see Figure 2) solely on haptic and proprioceptive feedback. We tested if deviations in this distance estimations were predictable by the optimal Bayesian integration model.

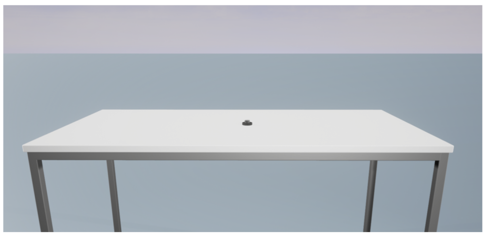

Figure 2: Table with a virtual button appearing for distance estimation by motor action.

4 Methods

4.1 Participants

Undergraduate students ($N = 56$; 35 women) volunteered to participate in the experiment in exchange for credit toward their research participation requirement. The age of the participants ranged from 18 to 27 years ($M = 20.32$, $SD = 1.71$). They were randomly assigned to one of the two experimental groups with 28 participants each. Written informed consent was obtained from all participants before participation in the study. This study received ethical approval from the institutional ethics committee.

4.2 Apparatus

The experimental setup included an office chair placed in front of a rectangular office table. The chair was placed at a marked distance from the table center. During the experiment, the participant wore a head-mounted display (HTC Vive). Stereoscopic images were rendered at 90 Hz by an Intel Xeon E3 3.40 GHz, 16 GB RAM computer with an NVIDIA GeForce GTX 980 Ti graphics card. A position sensor (HTC Vive Controller) was placed in a defined position as a reference for initially aligning the virtual and real table. During the experiment, the position of the virtual and real table was locked. The integration of sensor data and the visualization of the virtual environment was realized with the Epic Games Unreal Engine 4.14. The virtual stimuli were created with Autodesk Maya 2017.

4.3 Materials

During the experiment, a digital replication of a table standing on a blank, infinite floor was presented in the head-mounted display (see Figure 1). A virtual button was intermittently displayed in the center of the virtual tabletop (see Figure 2). This virtual environment was presented in a stereoscopic head-mounted display where the viewpoint adapted to the relative position of the head-mounted display. This allowed the participants to look around in the virtual environment by moving their head. The virtual table had the same size as the real table and was placed on the virtual floor that was at the same height as the real floor.

4.4 Measures

4.4.1 Midimmersion Presence

A brief one-item mid-immersion measure of presence, introduced by Bouchard et al. [8], was recorded twice during the exposure to the virtual environment. Participants answered the following question out loud on a scale of 0 (*not at all*) to 10 (*totally*): "To what extent do you feel present in the virtual environment right now?" All participants were told that "Presence is defined as the subjective impression of really being there in the virtual environment". There is evidence that brief one-item presence measures during immersion are more sensitive to the subjective feeling of presence than post-immersive questionnaires [8, 13, 54]. The reliability of a similar presence rating was shown in Hendrix and Barfield [17] and the ability of this and similar measures to detect treatment effects [8, 20, 25] gives preliminary evidence of its validity.

4.4.2 Postimmersion Presence Questionnaires

Immediately after the exposure to the virtual environment, two questionnaires were conducted to assess the construct spatial presence: first, the MEC-Spatial Presence Questionnaire (MEC-SPQ) [63] and second the Igroup Presence Questionnaire (IPQ) [49].

The MEC-SPQ is derived from a model of spatial presence that distinguishes presence, involvement, and attention [5, 66]. Only the group of process variables which model the direct formation of spatial presence (attention allocation (AA), spatial situation model (SSM), spatial presence: self-location (SPSL), spatial presence: possible actions (SPPA)) were assessed. The group of variables addressing enduring personality factors (domain specific interest, visual-spatial imagery, absorption), and the thereof affected group of variables referring to states and actions (higher cognitive involvement, suspension of disbelief) were excluded to minimize the time-offset from immersion to filling out the second questionnaire. Each MEC-SPQ subscale consists of eight items with a five-point Lickert scale. The reliability of each MEC-SPQ subscale was preliminary assessed. The Conbrach's alphas of the assessed subscales were the following [5]: AA $\alpha = 0.93$, SSM $\alpha = 0.90$, SPSL $\alpha = 0.92$, SPPA $\alpha = 0.81$. The validity of the measure was supported by the correlation between subscales [5] and by notable correlations with related measures of presence [3, 5, 39]. High sensitivity, capable of distinguishing between multiple levels of presence across different types of media has been shown [5, 39].

The IPQ was conducted after the MEC-SPQ. It aims to measure presence in virtual environments. The IPQ was constructed using an exploratory factor analysis on a combination of existing and newly generated items from presence questionnaires [49]. The measure consists of three subscales which were termed spatial presence, involvement, and realness, each consisting of four items with a seven-point Lickert scale. An initial confirmatory factor analysis supported the measure's reliability and validity [49]. The measures sensitivity to distinguish between several levels of presence was shown in multiple studies.

4.4.3 Distance Estimation by Motor Action

A visual stimulus displaying a button with 1 cm diameter and 1 cm height was presented at the center of the visually displayed table top. Within the procedure of the experiment, the participants were instructed to put the finger in the position where they saw the button. The deviation in the posterior-anterior direction was measured manually.

4.5 Experimental Manipulation

The experiment followed a single-blind mixed-group design with one two-level repeated measures factor prior and post presentation of haptic information one two-level between factor: in the experimental condition, the virtual table was placed with a posterior-anterior offset of 20 cm to the real table, where the virtual table was more distant to

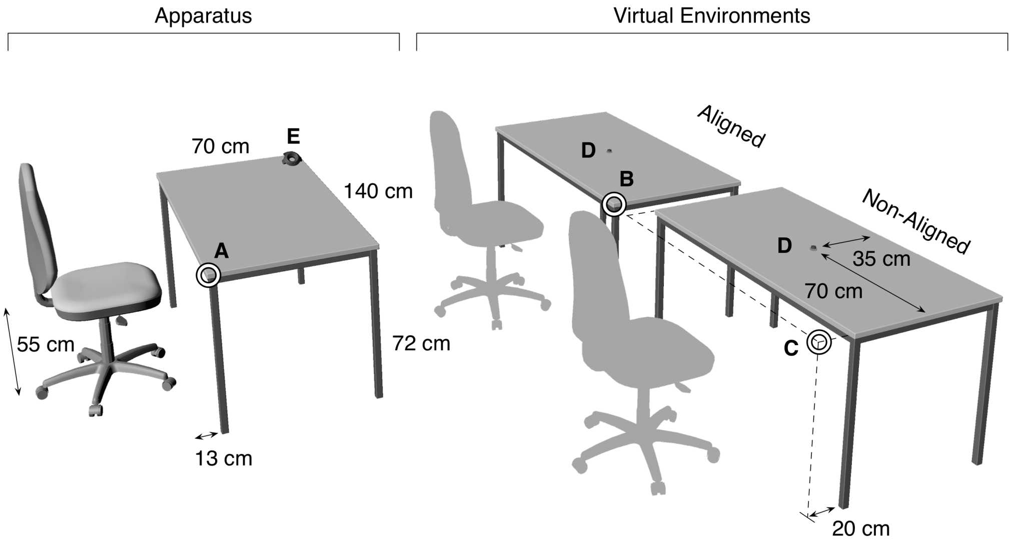

Figure 3: The participant is exposed to a virtual replica of the table that is either in the same position (aligned condition, where the virtual location **B** matches the reference location **A**) or translated by 20 cm (non-aligned condition, where the virtual location **C** matches **A**). The offset between the virtual and the real table is controlled using a six degrees of freedom sensor (**E**). A button is displayed in the virtual environments (**D**) for the distance estimation.

the chair than the real table. In the control condition, the virtual table was placed in the same position as the real table. In both conditions, the height and lateral position of the virtual table matched that of the real table.

4.6 Procedure

For each of the two conditions the five dependent variables were measured in the following chronological order: Participants were seated in the office chair that was initially rotated 180° away from the table and was instructed to put on the head-mounted display. Then they were instructed to rotate the chair to the table behind them and to explore the table visually for 30 s. The one-item mid-immersion measure was then conducted for the first time to obtain the baseline immersion. Following this, participants were instructed to explore the front-side of the table visually and with both their hands for 30 s, and to remove their hands afterward. The second one-item mid-immersion presence measure was then conducted. The virtual button was presented in the center of the virtual tabletop for 5 s. Afterwards, the participants were instructed to close their eyes, and then to touch the table at the point where they saw the virtual button with their preferred index finger with a continuous pointing gesture while avoiding to touch the table in any other way. The position where the finger touched the table was measured. After the experiment, the participants were instructed to enter another room and to fill out the two post-immersion presence questionnaires IPQ and MEC-SPQ. The experimental procedure is illustrated in Figure 4.

4.7 Statistical Analysis

Presence ratings are operationalized by composed Likert scale data, that was analyzed at the interval measurement scale [6]. Before analysis, all scales were tested for normality by applying Shapiro-Wilk tests. In case the normality assumption held true, one-tailed paired Student's t-tests were calculated to compare within-group differences, and unpaired Welch's t-tests were calculated to compare between-group differences, as proposed by [36]. Otherwise, if the normality assumption did not hold valid one-tailed Wilcoxon signed-rank tests were calculated to compare within-group differences and one-tailed Mann-Whitney U test were calculated to compare between-group differences. Distance estimations were compared against the two competing spatial reference systems. A priori significance level was set at $p < .05$ for all statistical tests. As a measure of effect size Cohen's d is reported for parametric test and Cohen's r for nonparametric tests, as described by Rosenthal [47].

5 Results

As no irregularities arose, all 56 participants were included in the following analysis.

5.1 Midimmersion Presence Ratings

Results of the Shapiro-Wilk normality test suggest that normality could not be assumed for mid-immersion presence ratings. There were significant effects for the factor pre-post visual-haptic matching in both the aligned $z = 1.86$, $p = .03$, and the non-aligned condition $z = 3.60$, $p < .001$ (see Figure Fig. 5). In the aligned condition, presence ratings were higher after coherent haptic cues had been introduced ($M = 7.32$, $SD = 1.49$, $Mdn = 8$), compared to visual exposure alone ($M = 6.79$, $SD = 1.50$, $Mdn = 7$), showing a medium effect size ($r = .25$). Conversely, when non-aligned haptic cues had been introduced, we observed decreased presence ratings ($M = 5.0$, $SD = 2.36$, $Mdn = 5$), compared to visual exposure alone ($M = 6.64$, $SD = 1.93$, $Mdn = 7$), showing a large effect size ($r = .48$). There was a significant difference between groups in presence ratings after visual-haptic matching ($U = 383.00$, $z = 3.77$, $p < .001$) with a large effect size ($r = .50$), but no significant difference between groups in presence ratings prior to visual-haptic matching ($U = 164.00$, $z = 0.15$, $p = 0.88$).

5.2 Distance Estimation by Motor Action

Results of the Shapiro-Wilk normality test suggest that normality of the distance estimations in the non-aligned condition could be assumed ($W = 0.98$, $p = .89$). The deviation of distance estimations in the posterior-anterior direction was compared to the uni-modal visual and haptic spatial reference system. For the reference scale, the position of the visual cue was defined as zero-point. In the aligned condition the distance estimations ($M = 0.48$ cm, $SD = 4.47$ cm) did not significantly differ from the aligned visual and haptic spatial reference system (0 cm); $t(27) = 0.56$, $p = .57$. In

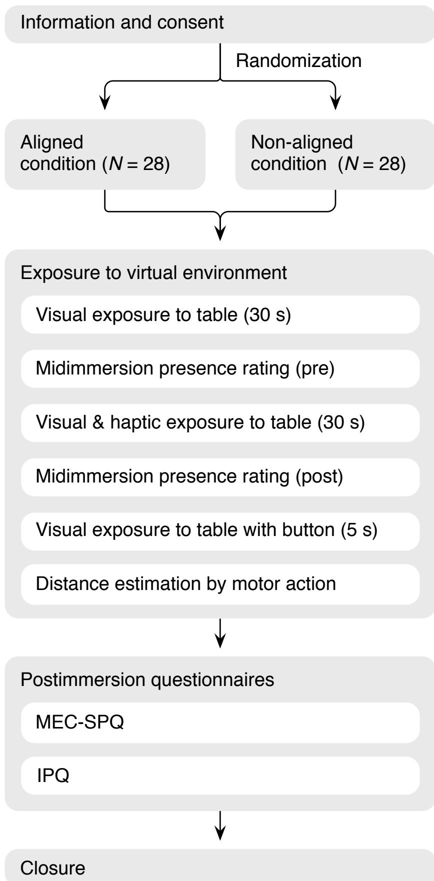

Figure 4: Illustration of the experimental procedure. In both conditions, a subjective mid-immersion presence rating was assessed after visual and after combined visual and haptic exposure to the stimulus. Afterwards, participant conducted a distance estimation task in the virtual environment and completed post-immersion presence questionnaires.

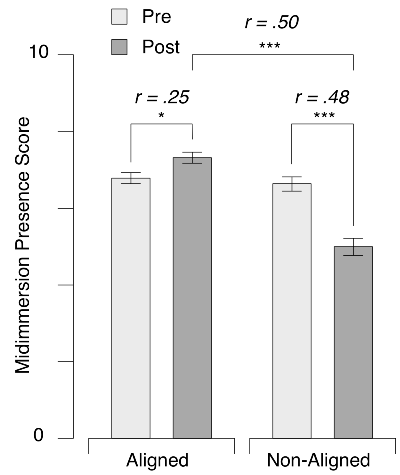

Figure 5: Score [mean ± SEM (error bars)] on the midimmersion presence item proposed by Bouchard et al. [8] before (light gray) and after introduction of haptic stimuli (dark gray). Participants showed a significant increase in the coherence condition (left) and a significant decrease in the incoherence condition (right). $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

the non-aligned condition, the distance estimations ($M = -15.0$ cm, $SD = 8.07$ cm) showed significant drifts away from both, the unimodal visual (0 cm; $t(27) = -9.66$, $p < .001$) and haptic (-20 cm; $t(27) = 3.22$, $p = .003$) spatial reference system, see Figure Fig. 6.

5.3 Post-Immersion Presence Ratings

In addition to presence questions asked during exposure, participants in both groups were required to answer presence-related questions after exposure. A comparison of responses of post-exposure responses between the aligned and non-aligned condition groups revealed the following results, also illustrated in Figures Fig. 7 and Fig. 8: Results of the Shapiro-Wilk normality test suggest that normality could not be assumed for the IPQ scales “general presence” and “spatial presence”. There was a significant difference in the IPQ “general presence” scores for the aligned ($M = 1.0$, $SD = 1.34$, $Mdn = 1$) and non-aligned ($M = 0.32$, $SD = 1.36$, $Mdn = 1$) conditions, showing greater “general presence” for the aligned condition with medium effect size ($r = .23$); $U = 290.00$, $z = 1.73$, $p = .04$. Also the IPQ “realness” scores were significantly greater in the aligned ($M = 1.55$, $SD = 0.83$) and non-aligned ($M = 0.95$, $SD = 1.08$) conditions, showing a medium effect size ($d = 0.62$); $t(50.72) = 2.31$, $p = .01$. The IPQ “spatial presence” scores showed no significant difference between the aligned condition ($M = 2.20$, $SD = 1.18$, $Mdn = 2.40$) compared to the non-aligned condition ($M = 1.79$, $SD = 1.26$, $Mdn = 1.60$); $U = 308.00$, $z = 1.38$, $p = .08$.

The IPQ “involvement” scores showed no significant difference between the aligned condition ($M = 1.36$, $SD = 1.03$) and the non-aligned condition ($M = 1.41$, $SD = 1.21$); $t(52.66) = -.15$, $p = .88$. Results of the Shapiro-Wilk normality test suggest that normality could not be assumed for the MEC-SPQ scale “attention allocation”. There was a significant difference in the MEC-SPQ “spatial situation model” scores for the aligned ($M = 3.92$, $SD = 0.51$) and non-aligned ($M = 3.60$, $SD = 0.58$) conditions, showing a medium effect size ($d = 0.56$); $t(53.20) = 2.11$, $p = .02$. The MEC-SPQ “spatial presence: self location” scores showed a significant difference for the aligned ($M = 3.42$, $SD = 0.74$) and non-aligned ($M = 3.05$, $SD = 0.65$) conditions, showing a medium effect size ($d = 0.51$); $t(53.09) = 1.92$, $p = .03$. The MEC-SPQ “attention allocation” scores showed showed no significant difference between the aligned condition ($M = 3.65$, $SD = 0.40$, $Mdn = 3.69$) and the non-aligned condition ($M = 3.52$, $SD = 0.53$, $Mdn = 3.63$); $U = 316.50$, $z = 0.21$, $p = .10$. The MEC-SPQ “spatial presence: possible actions” scores also showed a showed no significant difference between the aligned condition ($M = 3.32$, $SD = 0.50$) and the non-aligned condition ($M = 3.12$, $SD = 0.51$); $t(53.98) = 1.46$, $p = .07$.

6 Discussion

Subjective presence ratings increased significantly with a medium effect size when haptic and visual feedback matched in the aligned condition. They decreased significantly with a marginally large effect size when haptic and visual feedback did not match. Overall presence ratings were compared between the two groups. Post-immersive presence reports for the IPQ scales “general presence” and “realness” and for the MEC-SPQ scales “spatial situation model” and “spatial presence: self-location” were significantly higher with medium effect sizes for the aligned condition group. For the remaining scales, a tendency in the predicted direction could be observed, except for the IPQ scale “involvement”. This can be explained by the exposed static environment which was not subject to event-related modifications. After all, the “involvement” construct describes “focusing [of] one’s energy and attention on a coherent set of stimuli or meaningfully related activities and events” [49].

There is evidence that continuous one-item mid-immersion presence measures are more sensitive to the subjective sensation of presence compared to post-immersion questionnaire [8, 13, 54]. The

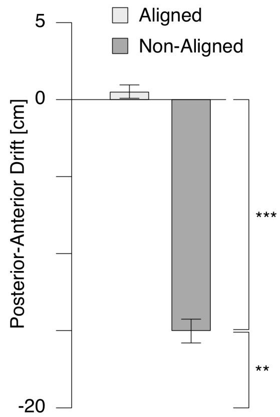

Figure 6: Distance estimation by motor action of the posterior-anterior axis, measured in centimeters (mean ± SEM) in the aligned (light gray) and non-aligned conditions (dark gray). In the non-aligned condition participants showed significant drifts away from the uni-modal visual and haptic spatial reference systems. **$p < .01$, ***$p < .001$.

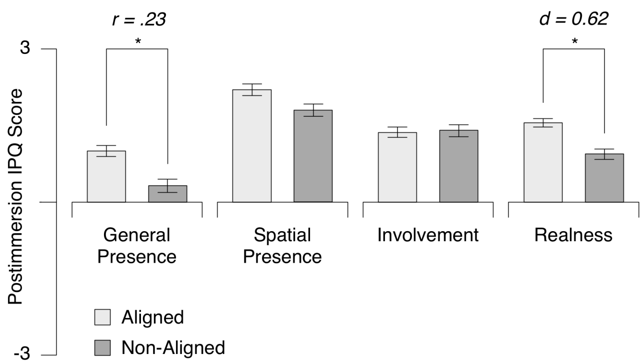

Figure 7: Score on the IPQ subscales in the coherence (light gray) and incoherence conditions (dark gray). Participants showed a significant lower score for general presence and realness in the incoherence condition. *$p < .05$.

reliability of post-immersion presence questionnaires is limited by inaccurate recall and memory effects such as recency and can be influenced by prior experiences [13,23,61]. These limitations of post-immersion presence questionnaires might explain why the between-group difference of the IPQ sub-scale "spatial presence" was not significant.

Overall, our findings support the hypothesis that presence is a function of sensory prediction accuracy [42,50,56]. In contrast to Dinh et al. [9], who reported increased presence ratings for conditions with passive tactile heat and wind sensations, the general effect could be further identified to be caused by coherent active haptic and visual feedback alone. Our findings are also in-line with results from scenarios which included virtual body ownership and agency [18,19,35,57,69], but we could rule-out the potential confounds induced by such approaches. The results provide empirical support for the importance of prediction processes on the emergence of presence in virtual environments independent of perceptions related to virtual body ownership and presence.

Significant drifts from the visual and the haptic spatial reference system were observed, and normality of the distribution was tested. These findings suggest that the conflicting visual and haptic information was merged into a coherent percept regarding the sensory integration model by Ernst and Bülthoff [11]. This assumption supports the hypothesis that the variation of presence ratings between the two conditions was not confounded by the cognitive representation of two distinct spatial reference systems in the non-aligned condition, hence suggesting that perceptual binding of the disparate cues occurred [45,60]. Assuming the model of Ernst and Bülthoff [11], the haptic modality was perceived as about three times as reliable as the visual modality. It seems reasonable that the perceived reliability of the sensory modalities is confounded by the knowledge of the virtual quality of the visual information. Nevertheless, in line with previous studies, this finding strongly underlines the relative importance of haptic information for the design of virtual environments.

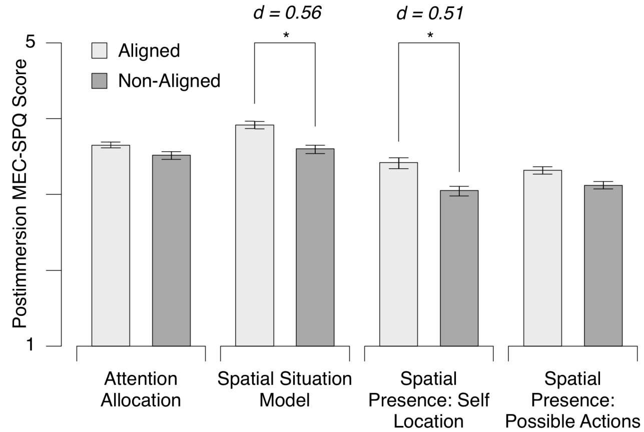

Figure 8: Score on the MEC-SPQ subscales in the coherence (light gray) and incoherence conditions (dark gray). Participants showed a significant lower results for spatial situation model and spatial presence: self location in the incoherence condition. *$p < .05$.

A modulated experience of presence in the real environment might be associated with the psychological construct of dissociation, including derealisation [2,38], which in the core is considered as a coping strategy for extreme stress situations [62]. As such, derealisation describes the experiences of unreality or detachment with respect to surroundings [1]. The condition is a poorly understood and under-researched dissociative syndrome, although high prevalence rates are observed [22]. The etiology of derealisation is unknown, but the neurological validity of the concept has been suggested [53]. The observed decrease in the perceived presence that was induced by incoherent visual and haptic sensory inputs in the present study potentially informs hypothesis about the neurological processes that result in pathological derealisation experiences. We observed that perceptual visually-anchored prediction errors might cause derealisation in a virtual environment. As such, in line with Seth [50], it seems reasonable to ask whether a failure of sensory prediction may too contribute to the emergence of derealisation in the real world. Based on the findings of the presented study we may hypothesize, that a cognitive model for derealisation is informed by prediction errors in the integration processes of multisensory information. Adverse psychological states like anxiety might trigger a process that leads to some form of disintegration of sensory input signals that moderates the dissociative sensation of derealisation. The conceptualization of derealisation as a continuum [21] is in line with the continuous model of multisensory integration regarding spatial and temporal integration.

6.1 Limitations

The experimental design did not correct for motor artifacts that might occur during the distance estimation task. Perceived distance is effected by optical variables as well as by the anticipated physical effort to perform an intended distance-relative action [44, 67]. Since the physical effort in the two conditions is not controlled, the distance might be overestimated in the incoherent condition. Notably, this effect would be expected to counteract the observed effect of distance underestimation.

We furthermore assume that in both conditions the target of the touch movement was perceived as reachable since perceived unreachability would be expected to counteract the observed effect of underestimation of the distance [68]. The tendency to underestimate distances during the exposure to a head-mounted display [65], seems to have no relevant impact at the scale of this experiment since the distance estimations in the coherence conditions were accurate. This study was limited by a modest sample size and reliance on self-reported outcomes by validated measures.

Given our short exposure time to visual and haptic stimuli, we do not know the long-term sustainability of the seen effects, nor dependency on total exposure time or repeated exposure. Also, the statistical significance achieved among many of the outcome measures in this trial may not necessarily equate to large effects for individuals. We did not employ a correction procedure for multiple outcome measures. Results were predominately and significantly in the direction of higher presence when visually-anchored prediction accuracy was high and lower presence, when prediction accuracy was low, which argues against isolated chance findings emerging simply due to multiple comparisons.

7 Summary

In conclusion, we developed an immersive VR-based experimental design to investigate the effect of visually-anchored prediction accuracy of haptic information on the subjective perception of presence. Our results significantly indicate that the prediction accuracy of haptic information contributes to a general perception of presence in a virtual environment. We found that high prediction accuracy increased presence ratings, while low prediction accuracy decreases presence ratings.

Our experimental design ensured the results to not be confounded by virtual body ownership and agency, often implicitly included in experimental designs based on visuotactile stimulation inspired by the classical rubber hand experiment [7]. Additionally, the design did include a distance estimation task to ensure the results to not be confounded by the cognitive representation of distinct spatial reference systems. The overall findings inform models for derealisation in the real world and underlines the importance of a coherent integration of haptic information into virtual environments [59].

7.1 Future Work

The presented results for the prediction accuracy of haptic information for the non-embodied condition provides a baseline to isolate potential impacts as caused by various degrees of embodiment, which we will continue to explore in future work. Additionally, the results motivate a closer look at the distinction of the presence construct into the place and the plausibility illusion. In fact, the chosen prediction accuracy is visually-anchored. This means it is heavily dependent on the mental spatial model and representation of the participants which one would certainly attribute to be affected by the place illusion. On the other hand, the derived prediction task could be attributed to be affected by the plausibility illusion, since it reflects on the expectation participants have concerning their spatial surrounding.

Acknowledgments

We thank Matthew McGinity, Daniel Gromer, and Daniel Roth for their advice and their comments on the manuscript. This work was supported by the German Federal Ministry of Education and Research (project InterMem, 16SV7322).

References

[1] A. P. Association et al. *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Pub, 2013.

[2] R. Banos, C. Botella, A. Garcia-Palacios, H. Villa, C. Perpiñá, and M. Gallardo. Psychological variables and reality judgment in virtual environments: the roles of absorption and dissociation. *CyberPsychology & Behavior*, 2(2):143–148, 1999.

[3] T. Baumgartner, L. Valko, M. Esslen, and L. Jäncke. Neural correlate of spatial presence in an arousing and noninteractive virtual reality: an eeg and psychophysiology study. *CyberPsychology & Behavior*, 9(1):30–45, 2006.

[4] T. Baumgartner, M. Willi, and L. Jäncke. Modulation of corticospinal activity by strong emotions evoked by pictures and classical music: a transcranial magnetic stimulation study. *Neuroreport*, 18(3):261–265, 2007.

[5] S. Böcking, A. Gysbers, W. Wirth, C. Klimmt, T. Hartmann, H. Schramm, J. Laarni, A. Sacau, and P. Vorderer. Theoretical and empirical support for distinctions between components and conditions of spatial presence. In *Proceedings of the VII. International Workshop on Presence–Presence*, pp. 224–231, 2004.

[6] H. N. Boone and D. A. Boone. Analyzing likert data. *Journal of extension*, 50(2):1–5, 2012.

[7] M. Botvinick and J. Cohen. Rubber hands 'feel' touch that eyes see. *Nature*, 391(6669):756–756, 1998.

[8] S. Bouchard, J. St-Jacques, G. Robillard, and P. Renaud. Anxiety increases the feeling of presence in virtual reality. *Presence: Teleoperators and Virtual Environments*, 17(4):376–391, 2008.

[9] H. Q. Dinh, N. Walker, L. F. Hodges, C. Song, and A. Kobayashi. Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In *Virtual Reality, 1999. Proceedings., IEEE*, pp. 222–228. IEEE, 1999.

[10] M. O. Ernst and M. S. Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870):429–433, 2002.

[11] M. O. Ernst and H. H. Bülthoff. Merging the senses into a robust percept. *Trends in cognitive sciences*, 8(4):162–169, 2004.

[12] C. R. Fetsch, G. C. DeAngelis, and D. E. Angelaki. Bridging the gap between theories of sensory cue integration and the physiology of multisensory neurons. *Nature Reviews Neuroscience*, 14(6):429–442, 2013.

[13] J. Freeman, S. E. Avons, D. E. Pearson, and W. A. IJsselsteijn. Effects of sensory information and prior experience on direct subjective ratings of presence. *Presence*, 8(1):1–13, 1999.

[14] E. J. Gibson. Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual review of psychology*, 39(1):1–42, 1988.

[15] J. J. Gibson. Observations on active touch. *Psychological review*, 69(6):477, 1962.

[16] J. J. Gibson. *The senses considered as perceptual systems.* Houghton Mifflin, Oxford, England, 1966.

[17] C. Hendrix and W. Barfield. Presence in virtual environments as a function of visual and auditory cues. In *Virtual Reality Annual International Symposium, 1995. Proceedings.*, pp. 74–82. IEEE, 1995.

[18] H. G. Hoffman, A. Garcia-Palacios, A. Carlin, T. A. Furness Iii, and C. Botella-Arbona. Interfaces that heal: Coupling real and virtual objects to treat spider phobia. *international Journal of Human-Computer interaction*, 16(2):283–300, 2003.

[19] H. G. Hoffman, A. Hollander, K. Schroder, S. Rousseau, and T. Furness. Physically touching and tasting virtual objects enhances the realism of virtual experiences. *Virtual Reality*, 3(4):226–234, 1998.

[20] H. G. Hoffman, E. J. Seibel, T. L. Richards, T. A. Furness, D. R. Patterson, and S. R. Sharar. Virtual reality helmet display quality

influences the magnitude of virtual reality analgesia. *The Journal of Pain*, 7(11):843–850, 2006.

[21] E. A. Holmes, R. J. Brown, W. Mansell, R. P. Fearon, E. C. Hunter, F. Frasquilho, and D. A. Oakley. Are there two qualitatively distinct forms of dissociation? a review and some clinical implications. *Clinical psychology review*, 25(1):1–23, 2005.

[22] E. C. Hunter, M. Sierra, and A. S. David. The epidemiology of depersonalisation and derealisation. *Social psychiatry and psychiatric epidemiology*, 39(1):9–18, 2004.

[23] B. E. Insko. Measuring presence: Subjective, behavioral and physiological methods. In G. Riva, F. Davide, and W. IJsselsteijn, eds., *Being There: Concepts, effects and measurement of user presence in synthetic environments*, pp. 110–118. Ios Press, Amsterdam, Netherlands, 2003.

[24] M. Janczyk, S. Skirde, M. Weigelt, and W. Kunde. Visual and tactile action effects determine bimanual coordination performance. *Human Movement Science*, 28(4):437–449, 2009.

[25] S. E. Kober, J. Kurzmann, and C. Neuper. Cortical correlate of spatial presence in 2d and 3d interactive virtual reality: an eeg study. *International Journal of Psychophysiology*, 83(3):365–374, 2012.

[26] K. P. Körding and D. M. Wolpert. Bayesian decision theory in sensorimotor control. *Trends in cognitive sciences*, 10(7):319–326, 2006.

[27] M. Kuschel, F. Freyberger, M. Buss, and B. Färber. A presence measure for virtual reality and telepresence based on multimodal conflicts. In *Proceedings of PRESENCE 2007: The 10th Annual International Workshop on Presence*. Citeseer, 2007.

[28] J. Laarni, N. Ravaja, T. Saari, S. Böcking, T. Hartmann, and H. Schramm. Ways to measure spatial presence: Review and future directions. In *Immersed in Media*, pp. 139–185. Springer, 2015.

[29] S. J. Lederman and R. L. Klatzky. Hand movements: A window into haptic object recognition. *Cognitive psychology*, 19(3):342–368, 1987.

[30] S. J. Lederman and R. L. Klatzky. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, 71(7):1439–1459, 2009.

[31] K. M. Lee. Presence, explicated. *Communication theory*, 14(1):27–50, 2004.

[32] M. Lombard and T. Ditton. At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication*, 3(2):0–0, 1997.

[33] M. Lombard and M. T. Jones. Defining presence. In *Immersed in Media*, pp. 13–34. Springer, 2015.

[34] J. M. Loomis and S. J. Lederman. Tactual perception. *Handbook of perception and human performances*, 2:2, 1986.

[35] M. Meehan, B. Insko, M. Whitton, and F. P. Brooks Jr. Physiological measures of presence in stressful virtual environments. *ACM Transactions on Graphics (TOG)*, 21(3):645–652, 2002.

[36] B. K. Moser and G. R. Stevens. Homogeneity of variance in the two-sample means test. *The American Statistician*, 46(1):19–21, 1992.

[37] J. Munzert, B. Lorey, and K. Zentgraf. Cognitive motor processes: the role of motor imagery in the study of motor representations. *Brain research reviews*, 60(2):306–326, 2009.

[38] C. D. Murray, J. Fox, and S. Pettifer. Absorption, dissociation, locus of control and presence in virtual reality. *Computers in Human Behavior*, 23(3):1347–1354, 2007.

[39] L. Nacke and C. A. Lindley. Flow and immersion in first-person shooters: measuring the player's gameplay experience. In *Proceedings of the 2008 Conference on Future Play: Research, Play, Share*, pp. 81–88. ACM, 2008.

[40] J. K. O'Regan et al. What it is like to see: A sensorimotor theory of perceptual experience. *Synthese*, 129(1):79–103, 2001.

[41] J. K. O'Regan and A. Noë. A sensorimotor account of vision and visual consciousness. *Behavioral and brain sciences*, 24(05):939–973, 2001.

[42] M. Parola, S. Johnson, and R. West. Turning presence inside-out: Metanarratives. *Electronic Imaging*, 9, 2016.

[43] D. R. Proffitt. Embodied perception and the economy of action. *Perspectives on psychological science*, 1(2):110–122, 2006.

[44] D. R. Proffitt, J. Stefanucci, T. Banton, and W. Epstein. The role of effort in perceiving distance. *Psychological Science*, 14(2):106–112, 2003.

[45] A. Revonsuo. Binding and the phenomenal unity of consciousness. *Consciousness and cognition*, 8(2):173–185, 1999.

[46] I. Rock and J. Victor. Vision and touch: An experimentally created conflict between the two senses. *Science*, 143(3606):594–596, 1964.

[47] R. Rosenthal. Parametric measures of effect size. *The handbook of research synthesis*, pp. 231–244, 1994.

[48] M. V. Sanchez-Vives and M. Slater. From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, 6(4):332–339, 2005.

[49] T. Schubert, F. Friedmann, and H. Regenbrecht. The experience of presence: Factor analytic insights. *Presence*, 10(3):266–281, 2001.

[50] A. K. Seth. A predictive processing theory of sensorimotor contingencies: Explaining the puzzle of perceptual presence and its absence in synesthesia. *Cognitive neuroscience*, 5(2):97–118, 2014.

[51] A. K. Seth, K. Suzuki, and H. D. Critchley. An interoceptive predictive coding model of conscious presence. *Frontiers in psychology*, 2, 2011.

[52] L. Shams, Y. Kamitani, and S. Shimojo. Illusions: What you see is what you hear. *Nature*, 408(6814):788–788, 2000.

[53] M. Sierra, F. Lopera, M. Lambert, M. Phillips, and A. David. Separating depersonalisation and derealisation: the relevance of the "lesion method". *Journal of Neurology, Neurosurgery & Psychiatry*, 72(4):530–532, 2002.

[54] M. Slater. Measuring presence: A response to the witmer and singer presence questionnaire. *Presence: Teleoperators and Virtual Environments*, 8(5):560–565, 1999.

[55] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535):3549–3557, 2009.

[56] M. Slater, P. Khanna, J. Mortensen, and I. Yu. Visual realism enhances realistic response in an immersive virtual environment. *IEEE computer graphics and applications*, 29(3), 2009.

[57] M. Slater, D. Pérez Marcos, H. Ehrsson, and M. V. Sanchez-Vives. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience*, 3:29, 2009.

[58] M. Slater and M. Usoh. Representations systems, perceptual position, and presence in immersive virtual environments. *Presence: Teleoperators & Virtual Environments*, 2(3):221–233, 1993.

[59] M. A. Srinivasan and C. Basdogan. Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, 21(4):393–404, 1997.

[60] A. Treisman. The binding problem. *Current opinion in neurobiology*, 6(2):171–178, 1996.

[61] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence: Teleoperators and Virtual Environments*, 9(5):497–503, 2000.

[62] B. A. van der Kolk, S. Roth, D. Pelcovitz, S. Sunday, and J. Spinazzola. Disorders of extreme stress: The empirical foundation of a complex adaptation to trauma. *Journal of traumatic stress*, 18(5):389–399, 2005.

[63] P. Vorderer, W. Wirth, F. R. Gouveia, F. Biocca, T. Saari, F. Jäncke, S. Böcking, H. Schramm, A. Gysbers, T. Hartmann, et al. Mec spatial presence questionnaire (mec-spq): Short documentation and instructions for application. *Report to the European Community, Project Presence: MEC (IST-2001-37661)*, 3, 2004.

[64] R. Welch and D. Warren. Intersensory interactions. *Handbook of perception and human performance.*, 1:25–1, 1986.

[65] P. Willemsen, M. B. Colton, S. H. Creem-Regehr, and W. B. Thompson. The effects of head-mounted display mechanics on distance judgments in virtual environments. In *Proceedings of the 1st Symposium on Applied perception in graphics and visualization*, pp. 35–38. ACM, 2004.

[66] W. Wirth, T. Hartmann, S. Böcking, P. Vorderer, C. Klimmt, H. Schramm, T. Saari, J. Laarni, N. Ravaja, F. R. Gouveia, et al. A process model of the formation of spatial presence experiences. *Media psychology*, 9(3):493–525, 2007.

[67] J. K. Witt, D. R. Proffitt, and W. Epstein. Perceiving distance: A role of effort and intent. *Perception*, 33(5):577–590, 2004.

[68] J. K. Witt, D. R. Proffitt, and W. Epstein. Tool use affects perceived distance, but only when you intend to use it. *Journal of experimental psychology: Human perception and performance*, 31(5):880, 2005.

[69] Y. Yuan and A. Steed. Is the rubber hand illusion induced by immersive virtual reality? In *Virtual Reality Conference (VR), 2010 IEEE*, pp. 95–102. IEEE, 2010.