Impact of Visual-Haptic Spatial Discrepancy on Targeting Performance

Chang-Gyu Lee, Ian Oakley, Eun-Soo Kim, and Jeha Ryu, *Member, IEEE*

***Abstract*—This paper presents a comprehensive study of the impact of visual-haptic spatial discrepancies on human performance in a targeting task conducted in a visual-haptic virtual and augmented environment. Moreover, it explores whether the impact of this effect varies with two additional variables: 1) haptic wall stiffness and 2) visual cursor diameter. Finally, we discuss the relative dominance of visual and haptic cues during a targeting task. The results indicate that while the spatial discrepancies studied exerted a small effect on the time required to perform targeting, they impacted the absolute errors considerably. Additionally, we report that haptic wall stiffness has a significant effect on absolute errors while the visual cursor diameter has a significant effect on movement time. Finally, we conclude that while both visual and haptic cues are important during targeting tasks, haptic cues played a more dominant role than visual cues. The results of this paper can be used to predict how human targeting performance will vary between systems, such as those using haptically enabled virtual reality or augmented reality technologies that feature visual-haptic spatial discrepancies.**

***Index Terms*—Augmented reality (AR), force feedback, haptic interfaces, performance evaluation, surgery, virtual reality (VR).**

I. Introduction

HUMANS perceive rich, coherent multisensory feedback comprised of sights, sounds, smells, tastes, and haptic sensations while manipulating objects in real environments. Many digital, virtual, or augmented environments seek to emulate this richness and incorporate multisensory feedback, most typically combinations of visual, auditory, and haptic cues. Indeed, the benefits of providing multimodal feedback are well reported and substantial. For example, mixing visual, audio, and haptic information improves task performance in terms of both efficiency (e.g., task completion time) and accuracy (e.g., error rates) during a drag-and-drop task [1]. Similar improvements in reaction time and mean accuracy were observed during a mobile phone dialing task conducted on a commercial touch screen device [2]. Additionally, improvements to task completion time and selection distance error were observed during target acquisition tasks [3]. In addition, faster movement times were achieved during a reaching and grasping task when auditory and/or graphic contact cues were added to a haptic cue [4].

However, achieving such improvements requires a demanding level of precision as even objectively small disturbances in the coherence of multisensory feedback, such as temporal delays between cues delivered to different sensory modalities, can lower task performance. For example, Chaudhari *et al.* [5] documented the effects of network-induced haptic delay on the performance of a pursuit-tracking task in which participants had to move a virtual cube such that it followed the path (and matched the velocity) of a reference cube. The results revealed that haptic delays of as little as 14 ms disrupted participants' accuracy. Similarly, Jay and Hubbold [6] investigated the effects of delaying haptic and/or visual feedback during a reciprocal tapping task. They found that visual delays of 94 ms increased both intertap interval and number of targets missed, whereas, haptic delays of 187 ms increased only the intertap interval. In a higher level and more complex task, Thompson *et al.* [7] measured the completion time during simulated surgical procedures, such as grasp-and-transfer and hemostasis, under conditions of various visual and haptic delays. The results showed that nontrivial time delays (e.g., 0.6 and 1.2 s) degraded the performance of surgical tasks.

While these studies highlight the importance of temporal synchronization of cues, in visual-haptic environments, correctly aligning the temporal delivery of information is insufficient in creating a coherent multisensory representation—precise spatial alignment of cues is also required in order to ensure realism and to foster a high level of immersion. This is particularly important in application areas such as medical training simulators [8]–[13]. These application domains require precise spatial coherence between visual and haptic feedback in order to provide valuable and effective training experiences and to achieve realistic, compelling displays of virtual contents. However, this paper argues that achieving this required level of spatial precision is a challenging task in many common application scenarios. Note that,

Manuscript received March 31, 2015; accepted July 12, 2015. This work was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning under Grant 2011-0030079. This paper was recommended by Associate Editor S. Nahavandi.

The material shows a participant during an experiment. This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors.

C.-G. Lee is with the Department of Medical System Engineering, Human Robotics Laboratory, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea (e-mail: lcgyu@gist.ac.kr).

I. Oakley is with the School of Design and Human Engineering, Ulsan National Institute of Science and Technology, Ulsan, 689-798, Korea (e-mail: ian.r.oakley@gmail.com).

E.-S. Kim is with the HoloDigilog Human Media Research Center, 3D Display Research Center, Kwangwoon University, Seoul 139-701, Korea (e-mail: eskim@kw.ac.kr).

J. Ryu is with the School of Mechatronics, Human Robotics Laboratory, Gwangju Institute of Science and Technology, Gwangju, 500-712, Korea (e-mail: ryu@gist.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMC.2015.2468675

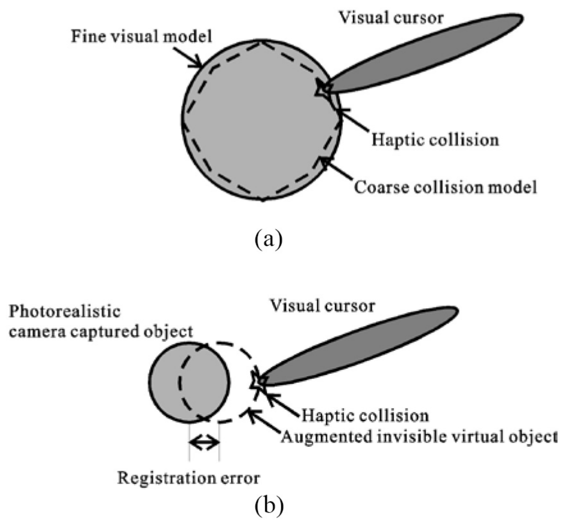


Fig. 1. Rationale of spatial discrepancy. Spatial discrepancy in haptic (a) VR system and (b) AR system.

in closely related work, Widmer and Hu [14] investigated the effects of the alignment between a haptic device and visual display on the perception of object stiffness with three different alignments (same-location, vertical alignment, and horizontal alignment) These alignments, however, have zero spatial discrepancy (in other words, visual and haptic cues are spatially coherent). On the other hand, this paper investigates the impact of nonzero spatial discrepancies on targeting performance with consistent horizontal alignment.

In fact, errors in spatial alignment between visual and haptic cues exist in many practical haptic virtual reality (VR) or augmented reality (AR) systems. For example, haptic VR systems such as medical training simulators [9]–[12] are usually composed of different model levels: a fine visual model for a realistic graphical display and a coarse collision model for high-speed collision detection [9]–[11]. In this multiresolution case, with direct haptic rendering, visual-haptic spatial discrepancy occurs because the haptic collision occurs between the coarse collision model and a visual cursor representing the physical haptic device end-effector whereas the visual collision takes place between the fine visual model and the visual cursor [see Fig. 1(a)] [9], [10]. A fine visual model and a coarse collision model can also be used with a visual cursor (e.g., a complex surgical tool) instead of a simple visual cursor [11].

Visual-haptic spatial discrepancies may also occur even when visual and collision models share the same level of detail. This is because collision detection processes are frequently approximated (e.g., collision between two bounding spheres). In these cases, users will expect collisions when the visual model and the visual cursor come into contact but differences between the representations maintained for each modality may result in inconsistency between the feedback presented visually and that presented haptically. Even though using graphical processing unit for collision detection and adopting a bounding volume hierarchy may avoid spatial discrepancies for relatively simple objects (for example, scenes with tens of thousands nodes [15] and hundreds of intersecting sphere pairs [16]), we argue that for more complex objects with millions of meshes, spatial discrepancies are inevitable with the current state-of-the-art computing systems.

Visual-haptic spatial discrepancies can also occur in haptic AR systems. For instance, Rasool and Sourin [13] presented photorealistic captured scenes for visual display and used invisible virtual objects for haptic display. The combination of these representations was proposed due to the difference in visual quality between the real scene and the virtually simulated scene. In this configuration, an invisible virtual object (e.g., a simple virtual face model to generate haptic sensations) is superimposed on a photorealistic camera-captured object (e.g., a real face). As illustrated in Fig. 1(b), spatial discrepancy occurs not only because of differences between the models, but also due to registration errors [17] in the algorithms that align the invisible virtual object on the photorealistic camera-captured object. In this case, users will expect haptic collision when the photorealistic camera-captured object and the visual cursor come into visual contact but registration errors in aligning the invisible virtual object will lead to inconsistency in the feedback provided in visual and haptic modalities.

In case of indirect haptic rendering, the virtual-coupling concept [18] is usually used. In this case, it seems that no spatial discrepancies may occur because the pose of a virtual tool is constrained to stay on the boundary of the virtual object. Spatial discrepancies, however, may also appear even in this case. In the multiresolution case, haptic collision detection is performed with a coarse haptic model, not a fine visual model as in the direct haptic rendering. Therefore, the virtual tool can penetrate into or be apart from the fine visual model when a haptic device collides with a coarse haptic model [see Fig. 1(a)]. Even in cases involving the same level of detail in the visual and haptic models, a collision between two bounding spheres can generate penetration or separation of the virtual haptic tool with the visual representation of the virtual object as in direct haptic rendering. Finally, in haptic AR systems, there is a registration error between a camera-captured scene and an invisible virtual object. As in the direct haptic rendering, haptic collision detection is performed with the invisible virtual object. Therefore, the virtual tool can penetrate into or be apart from the camera-captured scene [see Fig. 1(b)].

These misalignments can be disruptive as users typically expect zero spatial discrepancy between visual and haptic cues when exploring objects with a kinesthetic haptic device—this is both natural situation in the real world and situation that existing haptic VR and AR systems attempt to achieve. The quantitative impact of such spatial discrepancies can be substantial. For example, mean time per tap was increased during a Fitts' tapping task [19] in which participants performed reciprocal tapping between a series of virtual cylinders in a configuration with a varying degree of artificially generated spatial discrepancy. We also described a preliminary investigation of performance degradation during a targeting task with various levels of spatial discrepancy [20]. In this paper, we used the index of error correction effectiveness [21] as a performance criterion and found that a spatial discrepancy of 2 mm or less had no impact on targeting performance, whereas spatial discrepancies greater than 2 mm led to detectable and disruptive degradations to performance.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

While this literature highlights the negative effects of spatial discrepancies between visual and haptic cues, it does not yet paint a complete picture. Therefore, this paper seeks to address this omission and provide a more in-depth description of the impact of tightly controlled spatial discrepancies on performance of a typical targeting task based on the standard measurement criteria of task completion time, errors, and maximum reaction force. Furthermore, it explores this issue in tandem with two additional stimulus variables, the stiffness of haptic object and the diameter of visual cursor (or representation of the haptic device end-effector). These are intrinsic properties of visual-haptic simulations that frequently vary across different applications and objects in the real world.

The rationale for selecting a targeting task for the current investigation is that accurate aiming and positioning is a precursor to most other haptic tasks—before any action can be initiated in a simulation, a user must reach the appropriate location to take that action. In general, users also seek to complete targeting operations optimally—rapidly and with low error rates. In haptic simulations, accurate targeting can be imperative—for example, in the application domain of medical simulation, nurses making injections, dentists applying their tools or laparoscopic surgeons positioning a blade all involve precise targeting of small locations as a precursor to the main task.

By characterizing and analyzing targeting performance in this way we believe the results of this paper will be relevant to, and can help inform the design of, systems in a wide variety of application domains relying on closely corresponding visual-haptic scenes, such as haptic VR or AR systems. Specifically, we expect the results of this paper can be used to determine necessary system capabilities in terms of registration accuracy (essentially serving as a functional requirement) and to predict user performance when interacting with a system with known levels of spatial discrepancy, haptic object stiffness, and visual cursor diameter.

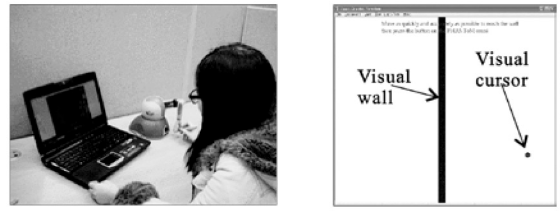
This paper makes the following contributions.

1) A systematic characterization of the performance degradation caused by visual-haptic spatial discrepancies when interacting with virtual or augmented realities.
2) A verification of the influence of haptic wall stiffness and visual cursor diameter on this performance degradation.
3) A discussion on relative dominance of visual and haptic cues during a targeting task.

The remainder of this paper is organized as follows. Section II introduces the experimental protocols including the specific system configuration and a description of the independent variables, procedures, measures, and demographics. In Section III, the results from the experiment are presented. Finally, Sections IV and V close this paper with a discussion of the results and a presentation of the key conclusions.

II. Experimental Protocol

This section introduces the detailed system configuration, stimulus variables studied, experimental procedures, measures, and participant demographics.



(a) (b)

Fig. 2. System configuration for experiments. (a) Configuration. (b) On-screen display.

A. System Configuration

During the study, participants sat in front of a 15.4-inch laptop monitor and manipulated the stylus of a PHANToM Omni (workspace: 160W $\times$ 120H $\times$ 70D mm) [22] with their dominant hand and without an arm rest, as illustrated in Fig. 2(a). We used this noncollocated configuration because the key motivating application area for this paper is minimally invasive surgery, a domain in which surgeons typically perform operations by manipulating instruments with their hands and observing the results on a noncollocated monitor. During the study, participants were requested to sit comfortably in front of the laptop with their eyes approximately 400–500 mm from the screen and to maintain this initial distance throughout the experiment. The content shown on screen was coherent with the physical dimensions of the haptic device: 1 mm of visually rendered content occupied 1 mm of physical space, and in the case of cursor control, 1 mm of physical movement equated to 1 mm of on-screen movement. During the study, neither visual nor sound cues from haptic device were blocked—participants could see their hands and the haptic device and also hear any sounds it made.

As illustrated in Fig. 2(b), the screen always showed a simple static visual wall with a width of 7.5 mm located at the center of the screen and a circular visual cursor representing the end point of PHANToM Omni stylus. This also served as a standard haptic interaction point (HIP). The scene also featured an invisible haptic wall with a width of 7.5 mm, which was modeled as a spring, and which generated contact reaction force when the visual cursor collided with it during tasks.

Even though the experiments in this paper involved a simple (flat) generic wall [as in Fig. 2(b)] as a representative collision model, we can obtain general conclusions because a complex object (composed of concave, flat, and convex surfaces) can be represented as a combination of small flat surface patches and because a point cursor is colliding with this small flat surface patch.

B. Experimental Design

Three variables were manipulated in a fully crossed experimental design: 1) the spatial discrepancy; 2) the stiffness of haptic wall; and 3) the diameter of visual cursor. All values of the independent variables are listed in Table I. The first variable is critical to our goal of exploring the impact of spatial discrepancies and the manipulation was achieved by systematically adjusting the position of the haptic wall relative to the statically positioned visual wall. Essentially, the haptic wall

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE I
VALUES OF THE INDEPENDENT VARIABLES

Independent variables	Spatial discrepancy (mm)	Stiffness of haptic wall (kN/m)	Diameter of visual cursor (mm)
Values	-3.0	0.4	1
	-1.5		
	0.0	0.7	3
	1.5	1.0	5
	3.0		

was moved among five possible relative locations: −3.0, −1.5, 0, +1.5, and +3.0 mm. We refer to situations when the haptic wall was farther from the participants' start point than the visual wall as positive spatial discrepancy and the inverse situation, when the haptic wall is closer than the visual wall, as negative spatial discrepancy. The range of spatial discrepancies considered was determined by system alignment accuracy values reported in recent haptic AR system [23]. This system typically reports registration errors of between two and three millimeters and, consequently, we sought to observe targeting performance with spatial discrepancies in this range.

The experiment was primarily intended to observe disturbances to typical targeting movements due to spatial discrepancies. As such, participants received no instructions about this presence of spatial discrepancies in the experiment. This was because we believe that people generally expect zero spatial discrepancy between visual and haptic representations when exploring objects with a kinesthetic haptic device as this is: 1) the situation in the real world and 2) the situation that existing haptic VR or AR systems attempt to achieve. In order to maintain this expectation throughout the study, we randomly presented nonzero spatial discrepancy trials within sequences of trials featuring zero spatial discrepancies. Specifically, each spatially discrepant trial (or target-trial) was presented within a trial-block featuring four other distractor-trials in which there was a perfect match between visual and haptic cues whereas the haptic wall stiffness and the visual cursor diameter were held constant. Furthermore, to prevent consecutive display of spatially discrepant trials, the target-trial never occupied the first spot in a trial-block, but was otherwise presented in a random order (ranging among second to fifth spots). This meant that participants were never certain when they would experience a target-trial, but also that they would never experience one immediately after a change in the other experimental variables. Finally, it also ensured that participants would not adapt their behavior to the cues presented in the target-trial [24].

The second stimulus variable we manipulated was the stiffness of the haptic wall. This paper used three stiffness levels: 0.4, 0.7, and 1.0 kN/m. These specific values were selected because they represent the typical stiffness of human body parts (ischial tuberosity, greater trochanter, posterior midthigh, and biceps brachii) [25]. They can also be rendered with a high level of stability given the inherent damping of the PHANToM Omni (the stably displayable stiffness in the x-axis is 1.26 kN/m) [22]. Therefore, any haptic stability algorithm, such as energy-bounding algorithm [26] was not

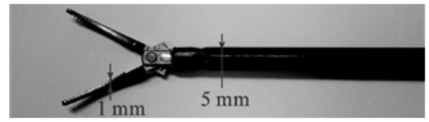


Fig. 3. Dimensions from laparoscopic surgical device.

applied throughout the study. The representative object stiffness values appear across a wide range of application scenarios and are particularly pertinent for the common haptic application area of surgical training. Additionally, the difference between each of these values exceeds commonly reported just noticeable differences for stiffness perception [27].

Note that both haptic and visual wall widths were selected to be 7.5 mm since the penetration of 7.5 mm into the haptic wall with a 0.4 kN/m stiffness can generate a reaction force of 3 N that should not exceed the maximum displayable force (3.3 N) of the PHANToM Omni [22] in order to avoid stiffness distortion. If a human subject penetrated more than this width, this trial is judged to be invalid because the deeper penetration will reduce the stiffness felt by the subject—consider the case of 10 mm penetration into the haptic wall with a 0.4 kN/m stiffness. In this situation, a haptic device with 3.3 N maximum reaction force will result in 0.33 kN/m stiffness (3.3 N divided by 10 mm) instead of the intended stiffness of 0.4 kN/m. For the highest stiffness of 1.0 kN/m, a greater force can be felt upon shallow contact with the higher stiffness haptic wall, so that subjects will judge whether a contact occurs or not without stiffness distortion effect that can occur in the lower stiffness case. Therefore, the haptic wall width of 7.5 mm is thought to be good enough for the intended experiments.

The third variable we manipulated was the diameter of the visual cursor. This was also varied among three levels: 1, 3, and 5 mm. These figures were selected as they represent typical dimensions of common surgical tools, as illustrated in Fig. 3. These tools were selected as a suitable source of visual cursor diameters as surgical training and telesurgery are a key focus for this paper and, in general, prominent and demanding application areas in the field of haptics.

Cursor size is an important variable because we used a standard three-degree-of-freedom point contact haptic rendering algorithm [28] to detect haptic collisions. With this algorithm, haptic collisions take place at the exact center of the visual cursor. Fig. 5 depicts the effects of visual cursor diameter on negative and positive spatial discrepancies when participants approach from the left side of the visual wall. For the negative spatial discrepancy [e.g., Fig. 4(a) and (c)], the haptic wall is outside the visual wall whereas for the positive spatial discrepancy [e.g., Fig. 4(b) and (d)], the haptic wall is inside the visual wall. As depicted in Fig. 4(a) and (b), if the radius of the visual cursor is larger than the magnitude of spatial discrepancy, there always is a partial overlap between visual cursor and visual wall at the moment of haptic collision. On the other hand, when the radius of visual cursor is smaller than the spatial discrepancy, the visual cursor either stays completely outside or penetrates completely into the visual wall as depicted in Fig. 4(c) and (d). These variations may influence the performance generated by spatial discrepancies.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

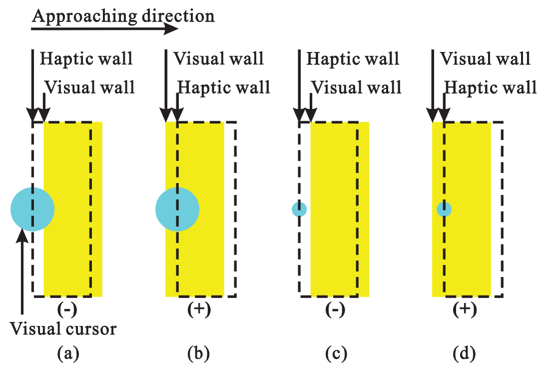


Fig. 4. Haptic collision and visual representation with respect to diameter of the visual cursor. (a) Larger visual cursor with negative spatial discrepancy. (b) Larger visual cursor with positive spatial discrepancy. (c) Smaller visual cursor with negative spatial discrepancy. (d) Smaller visual cursor with positive spatial discrepancy.

C. Procedure

Each individual targeting trial in the experiment was composed of three phases: 1) resting phase; 2) homing phase; and 3) targeting phase. In the resting phase (indicated by a red cursor), no reaction forces were applied and no measures were taken. A 20-mm square was shown to either the left or the right of the on-screen visual wall (indicating approaching direction, 50% of the trials in each direction). Participants' task in this phase was to move the visual cursor to the square side at their own pace and then press the button on the stylus of the PHANToM Omni.

The homing phase, shown by a change in the cursor color to blue, then began. During this phase, homing forces that move the haptic device toward the start point were applied for 1 s. These were directed toward a point to the left or the right of the on-screen visual wall—the start point (80 mm from the visual wall) of the participants' targeting movements in the study—and were intended to ensure that participants commenced targeting movements from a consistent pair of spatial locations that were equidistant from the visual wall. During the homing phase, the 20 mm square gradually shrunk at a rate calculated such that it disappeared entirely at the 1-s mark. When this occurred, the targeting phase began. The visualization of the gradually disappearing square was intended to allow participants to anticipate the beginning of the targeting phase and lower the contribution of reaction time to the targeting time measure.

During the targeting phase, the cursor turned green, the homing forces were immediately released and the participants' task was to "move as quickly and accurately as possible to reach the wall then press the button on the PHANToM Omni". The instructions were intentionally modality neutral: participants determined whether or not they had reached the wall according to their own interpretation of the visual and/or haptic cues they experienced. This choice was due to the fact that, in typical visual-haptic applications, no instructions about the relative importance of different modalities are provided to operators and we wanted to observe this kind of naturalistic performance. During the targeting phase, participants could move in the x (left–right), y (top–bottom), and z (near–far) axes whereas haptic feedback was presented only for the x-axis. Completing this task led to the start of the next trial.

During the targeting phase, three criteria were used to invalidate trials. First, if participants moved more than 5 mm from the start point during the homing phase, second, if participants pressed the button on the PHANToM Omni while not in contact with either the visual or the haptic wall, and third, if participants passed the center of visual cursor through the 7.5 mm haptic wall. These three criteria were established to ensure the targeting tasks during the study were typical, consistent, and comparable. They attempted to guarantee that movement distances in each trial were similar and that participants needed to target the edge of wall with a high degree of accuracy. Clicking in advance of contact, clicking after bouncing off the wall, and clicking after passing through the wall led to incomplete trials. In such cases, participants were required to rerun the trial-block.

As already explained in Section II-B, a trial-block is composed of four distractor-trials (zero spatial discrepancy) and one target-trial. Due to this structure, target-trials of zero spatial discrepancy were not presented as a separate condition. Instead, this data were captured from the measurements recorded in the large set of distractor-trials run during the experiment. This approach had the practical advantage of shortening the experiment.

Immediately prior to the experiment, each participant completed a training session featuring two spatial discrepancies (±3 mm), two haptic stiffness values (0.4 and 1.0 kN/m), and two visual cursor diameters (1 and 5 mm). These eight trial-blocks ($2 \times 2 \times 2$) were presented three times each, leading to a training session composed of a total of 24 trial-blocks or 120 targeting trials in total. After the training session participants took a 5-min break to prevent fatigue. The training session took about 10 min.

Each stimulus in the main experiment was presented five times. In accordance with this design, each participant completed a total of 180 trial-blocks (four spatial discrepancies × three stiffness levels × three cursor diameters × five repetitions) or a total of 900 individual targeting trials. The order of trial-blocks for the training session and the main experiment was fully randomized for each participant. Participants were required to take a 5-min break after every 30 trial-blocks to mitigate fatigue. The overall experiment took between 60 and 90 min including breaks.

D. Measures

Four measures of targeting performance were captured: movement time, absolute errors in the final position for the visual and the haptic walls, and maximum reaction force. During targeting, we expected participants to generate rapid, directed ballistic movements toward the visually observed target followed by fine-grained corrective adjustments upon arrival. We suggest that the existence of spatial discrepancy will lead to lengthier periods of fine-grained corrective adjustments and larger absolute errors.

Movement time was defined as the duration of targeting phase whereas the absolute errors for both walls referred to the absolute distance from the visual and the haptic walls to the center of the visual cursor at the time the trial ended. We measured two absolute errors because participants' task during experiments was "move as quickly and accurately as

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

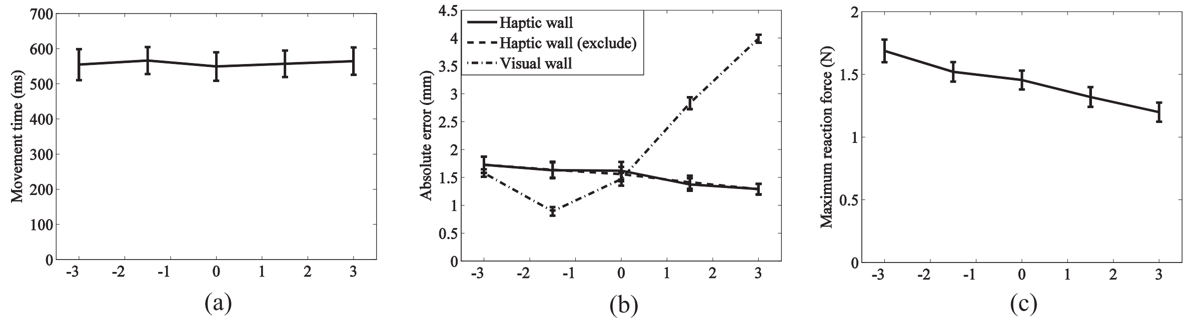


Fig. 5. Performance measures versus spatial discrepancy. (a) Movement time. (b) Absolute error. (c) Maximum reaction force.

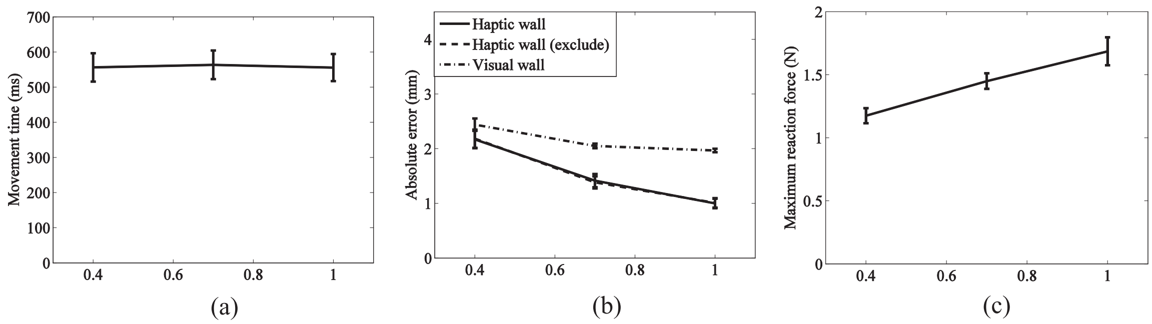


Fig. 6. Performance measures versus stiffness of the haptic wall. (a) Movement time. (b) Absolute error. (c) Maximum reaction force.

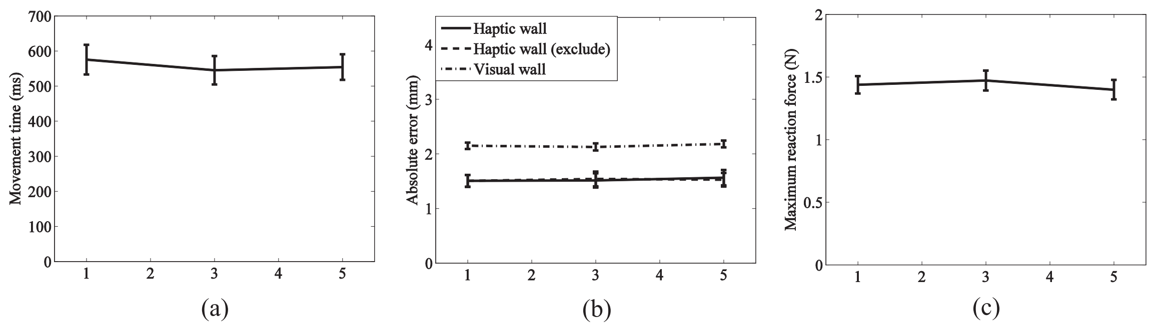


Fig. 7. Performance measures versus diameter of the visual cursor. (a) Movement time. (b) Absolute error. (c) Maximum reaction force.

possible to reach the wall…." As already described, there were two spatially discrepant walls (visual and haptic walls) and participants were able to use cues generated from either to judge completion of their targeting movements. Measuring both errors allows exploration of which cues were more important in participant's judgment of task completion. To further facilitate this analysis, we also captured the maximum reaction force generated during a trial [14], another measure of the magnitude of the haptic cues presented. These measures were selected to allow us to investigate how the three independent variables (spatial discrepancy, stiffness of haptic wall, and diameter of visual cursor) affect targeting movements. In addition, they allowed us to explore the relative weight placed on visual and haptic cues during judgments of the completion of a targeting movement.

E. Participants

Ten undergraduate students participated in the experiment. None of the participants were familiar with sophisticated haptic technologies. Four participants were male and six female, and their ages ranged between 18 and 21 [mean: 19.4, standard deviation (SD): 0.92]. One participant was left-handed.

III. Experimental Results

Figs. 5–7 show the experimental results of movement time, absolute errors for visual and haptic walls, and maximum reaction force versus the three independent variables of spatial discrepancy, the stiffness of the haptic wall, and the diameter of the visual cursor. Note that the results show mean values for each independent variable [e.g., Fig. 5(a) shows mean values over three stiffness values of haptic wall and over three diameters of the visual cursor]. Error bars in the figures denote standard errors.

To explore the differences in the data, three-way repeated-measure analysis of variance (RM-ANOVAs) were conducted for each experimental measure using statistical package for the social sciences [29] with five levels of spatial discrepancy, three levels of haptic wall stiffness, and three levels of visual cursor diameter. Table II shows the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
MAIN EFFECTS OF EACH VARIABLE

<table>
<tr><th>Variables / Measurements</th><th>Discrepancy</th><th colspan="3">Stiffness</th><th colspan="3">Diameter</th></tr>
<tr><td rowspan="3">Movement time</td><td rowspan="3">F(4, 36) = 1.280
p = 0.296</td><td colspan="3" rowspan="3">F(2, 18) = 0.571
p = 0.575</td><td colspan="3">F(2, 18) = 9.353
p = 0.002 **</td></tr>
<tr><td>1 vs 3</td><td>1 vs 5</td><td>3 vs 5</td></tr>
<tr><td>p = 0.003 **</td><td>p = 0.037 *</td><td>p = 0.895</td></tr>
<tr><td rowspan="3">Absolute error for visual wall</td><td rowspan="3">F(4, 36) = 258.524
p < 0.001 ***</td><td colspan="3">F(2, 18) = 22.782
p < 0.001 ***</td><td colspan="3" rowspan="3">F(2, 18) = 0.872
p = 0.435</td></tr>
<tr><td>0.4 vs 0.7</td><td>0.4 vs 1.0</td><td>0.7 vs 1.0</td></tr>
<tr><td>p = 0.005 **</td><td>p = 0.001 **</td><td>p = 0.146</td></tr>
<tr><td rowspan="3">Absolute error for haptic wall</td><td rowspan="3">F(4, 36) = 10.423
p < 0.001 ***</td><td colspan="3">F(2, 18) = 156.637
p < 0.001 ***</td><td colspan="3" rowspan="3">F(2, 18) = 0.591
p = 0.564</td></tr>
<tr><td>0.4 vs 0.7</td><td>0.4 vs 1.0</td><td>0.7 vs 1.0</td></tr>
<tr><td>p < 0.001 ***</td><td>p < 0.001 ***</td><td>p < 0.001 ***</td></tr>
</table>

-1.5	0.006**			
0.0	1.000	0.001**		
1.5	0.000***	0.000***	0.000***	
3.0	0.000***	0.000***	0.000***	0.000***
	-3.0	-1.5	0.0	1.5

(a)

-1.5	1.000			
0.0	1.000	1.000		
1.5	0.066	0.031*	0.020*	
3.0	0.013*	0.023*	0.071	1.000
	-3.0	-1.5	0.0	1.5

(b)

Fig. 8. Results of post-hoc pair-wise comparisons for spatial discrepancies. Absolute error for (a) visual wall and (b) haptic wall.

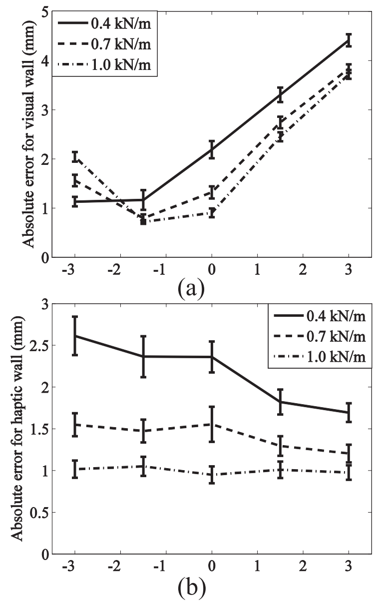


Fig. 9. Interaction plots between stiffness of the haptic wall and spatial discrepancy. (a) Absolute error for visual wall. (b) Absolute error for haptic wall.

TABLE III
INTERACTION EFFECTS BETWEEN VARIABLES

Variables / Measurements	Discrepancy * Diameter	Discrepancy * Stiffness	Stiffness * Diameter	Discrepancy * Stiffness * Diameter
Movement time	F(8, 72) = 1.684 p = 0.117	F(8, 72) = 0.640 p = 0.742	F(4, 36) = 0.189 p = 0.943	F(16, 144) = 0.781 p = 0.705
Absolute error for visual wall	F(8, 72) = 0.779 p = 0.622	F(8, 72) = 22.966 p < 0.001 ***	F(4, 36) = 0.407 p = 0.803	F(16, 144) = 1.001 p = 0.459
Absolute error for haptic wall	F(8, 72) = 1.064 p = 0.398	F(8, 72) = 5.451 p < 0.001 ***	F(4, 36) = 1.038 p = 0.401	F(16, 144) = 1.002 p = 0.459

TABLE IV
MEAN PEAK VELOCITIES IN EACH CONDITION

Spatial discrepancy (mm)	-3.0	-1.5	0.0	1.5	3.0
Peak velocity (m/s)	0.388 (0.081)	0.378 (0.077)	0.383 (0.072)	0.382 (0.072)	0.381 (0.074)
Stiffness of haptic wall (kN/m)	0.4	0.7	1.0		
Peak velocity (m/s)	0.386 (0.074)	0.379 (0.073)	0.384 (0.073)		
Diameter of visual cursor (mm)	1	3	5		
Peak velocity (m/s)	0.380 (0.072)	0.388 (0.076)	0.381 (0.071)		

RM-ANOVA results and the results of post-hoc pair-wise comparisons incorporating Bonferroni confidence internal adjustments for the variables of stiffness and diameter in cases where the RM-ANOVA main effects attained significance. Additionally, results of pair-wise comparisons for spatial discrepancies are presented in Fig. 8. Finally, the interaction effects from each of these tests appear in Table III. In order to verify interaction effects between the spatial discrepancy and the stiffness of the haptic wall in Table III, the interaction plots shown in Fig. 9 were obtained. Note that statistically significant differences are represented as follows: $p < 0.05^{*}$, $p < 0.01^{**}$, and $p < 0.001^{***}$.

During the experiments, participants generated an average peak velocity of 0.383 m/s (SD: 0.073 m/s) a figure that was relatively stable across all independent variables. These data are presented in Table IV. These values are similar to the previously reported value of 0.349 m/s, which was measured during a reaching and grasping task [4]. This suggests that participants in this paper generated typical targeting (or reaching) motions throughout the experiment.

Finally, it is also worth noting that although we designed the experiment to investigate three different stiffness levels of a haptic wall, stimuli were not correctly rendered in a small number of trials. Specifically, this occurred in situations when the calculated force value from the haptic wall exceeded 3.3 N, the maximum force output of the PHANToM Omni [22]. However, this incorrect rendering of stiffness was rare: 0.0% of trials for 0.4 kN/m, 0.6% of trials for 0.7 kN/m, and 1.07% of trials for 1.0 kN/m. We suggest that the impact of this issue on the final experimental results is negligible.

In addition, when the spatial discrepancy is positive and large, the center of the visual cursor is outside the haptic wall yet within the visual wall. In this case, the force participants perceived would be zero. However, as shown in Fig. 5(b), the absolute error for visual wall is larger than the spatial discrepancy, which means in most of the cases, the center of the visual cursor is within haptic wall. Although the latter case occurred in the vast majority of trials, we also explicitly examined the impact of trials in which the center of the cursor was outside the visual wall. Figs. 5(b), 6(b), and 7(b) show this subset of the data.

IV. DISCUSSION

This section discusses and interprets the experimental results in terms of performance with different spatial discrepancy levels, haptic wall stiffness values, and visual cursor diameters. In addition, relative dominance between visual and

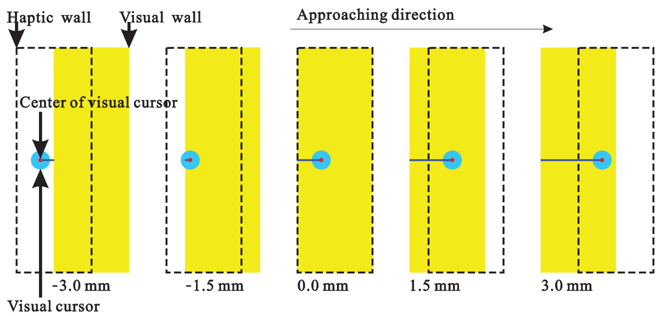


Fig. 10. Absolute error for visual wall with respect to spatial discrepancies considering consistent haptic wall penetration about 1.5 mm.

haptic cues is compared by using maximum reaction force. Finally, limitations of this paper are presented.

The different levels of spatial discrepancy did not influence movement time (rationale will be introduced below) across the study [see Fig. 5(a) and the second column of Table II]. However, there were statistically significant differences in the absolute errors for visual and haptic walls. The absolute error for visual wall in Fig. 5(b) shows that larger spatial discrepancies led to larger absolute error for visual wall (excluding a region between −1.5 and 0.0 mm). Note that this result is valid for any diameter of the visual cursor as seen in the second column of the interaction effects of Table III.

We also note that the absolute error for visual wall is smallest for the spatial discrepancy of −1.5 mm. This can be explained by considering the consistent penetration of the visual cursor into the haptic wall. Fig. 10 presents a visual representation of absolute error for the visual wall with respect to spatial discrepancies. In each case, penetration of visual cursor into the haptic wall is approximately 1.5 mm, as observed in the study [Fig. 5(b)], and the absolute error for visual wall is the distance between center of visual cursor and left boundary of visual wall. As this figure shows, in this configuration absolute error for visual wall is low for the spatial discrepancy of −1.5 mm—the consistent penetration of visual cursor into the haptic wall throughout the study results in a low absolute error for visual wall.

The absolute error for haptic wall, shown in Fig. 5(b), shrank from negative spatial discrepancy to positive spatial discrepancy. The decrease can be explained by considering the influence of the absolute error for visual wall. As seen in Fig. 11(a), with negative spatial discrepancies penetration of the visual cursor into the haptic wall decreases the absolute error for visual wall and increases the absolute error for haptic wall. In contrast, with positive spatial discrepancies [as seen in Fig. 11(b)], penetration of the visual cursor into the haptic wall increases absolute errors for both walls. We suggest that the decreasing trend in the absolute error for haptic wall is due to participants attempting to minimize the absolute error for the visual wall across the different spatial discrepancy conditions. Although this trend is roughly linear, post-hoc comparisons [Fig. 8(b)] indicate that the statistically significant differences are between positive and negative spatial discrepancies [dashed block of Fig. 8(b)].

Further insights into performance can be gained by analyzing the experimental results in more detail. Specifically, during

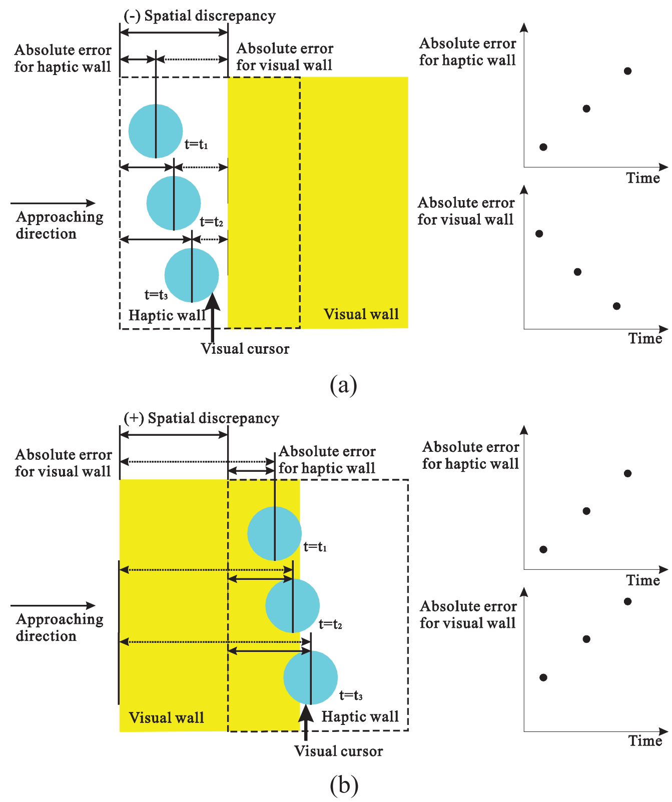


Fig. 11. Changes on the absolute errors for visual and haptic walls with respect to penetration of visual cursor into haptic walls. (a) Negative spatial discrepancy case. (b) Positive spatial discrepancy case.

a targeting task, both visual and haptic feedback play an important role in accurate movement termination. In this paper, the data shown in Fig. 5(c) suggest that participants' dependence on haptic feedback is larger than that on visual feedback. We conclude this because, if participants depended fully on visual feedback, maximum reaction force of positive spatial discrepancies would show low or zero values—participants may not reach the haptic wall. On the other hand, if participants depended fully on haptic feedback, maximum reaction force should show consistent values irrespective of spatial discrepancies. As seen in Fig. 5(c), however, neither pattern was observed. Instead, the mean maximum reaction force ranged roughly linearly between 1.687 N with −3.0 mm discrepancy to 1.201 N with +3.0 mm spatial discrepancy. We interpret this as participants seeking to vary their penetration into the haptic wall in order to stay closer to the visual wall. However, as this variation (0.486 N) was smaller than the maximum reaction force in the zero spatial discrepancy condition, we conclude that for the spatial discrepancies studied in this paper, the haptic cues played a more important role than the visual cues. Despite the dominance of haptic feedback suggested in Fig. 5(c), the absolute error for haptic wall decreased with positive spatial discrepancies, which suggests that visual feedback also played an important role in the task. Based on this analysis, we suggest that the targeting task was predominantly driven by participants attempting to reach the haptic wall, and their performance derived from a combination of the stiffness and location of haptic wall halting their movement.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE V
PENETRATION DEPTH VARIATION AT INITIAL IMPULSE MOTION AND AFTER CORRECTIVE MOTION

Diameter	A: Maximum penetration into the haptic wall (mm)	B: Absolute error for haptic wall (mm)	A - B (mm)
1	2.19	1.50	0.69
3	2.21	1.53	0.68
5	2.13	1.52	0.61

TABLE VI
PERCEPTUAL SPATIAL DISCREPANCIES

System-oriented spatial discrepancy (mm)		-3.0	-1.5	0.0	1.5	3.0
Diameter of visual cursor (mm)	Magnitude of positive shifting (mm)	Perceptual spatial discrepancies (mm)				
1	+0.5	-2.5	-1.0	0.5	2.0	3.5
3	+1.5	-1.5	0.0	1.5	3.0	4.5
5	+2.5	-0.5	1.0	2.5	4.0	5.5

The data also support fleshing out this suggestion. The third column of Table II shows that changes to the haptic wall stiffness led to statistically significant differences in both absolute errors for visual and haptic walls. In contrast, there was no significant effect on the movement time. The key observation is that higher stiffness levels led to smaller absolute errors for visual and haptic walls [see Fig. 6(b)]—the smallest absolute errors for visual and haptic walls, by 19.34% and 53.92%, respectively, were observed with the stiffest haptic wall. This is likely due to the fact that for lower stiffness values a larger penetration was required to reach the detection threshold for force perception. The experimental results shown mean maximum reaction forces of 1.148 N (SD: 0.524 N), 1.405 N (SD: 0.651 N), and 1.657 N (SD: 0.803 N) for the haptic wall stiffness levels of 0.4, 0.7, and 1.0 kN/m, respectively. These values are all higher than the detection threshold for force [30]. This result suggests that absolute errors for both walls were strongly dependent on the stiffness of the haptic wall.

The final main effect (as seen in the fourth column of Table II) shows that changes in the visual cursor diameter led to statistically significant differences in the movement time but not in the absolute errors for the visual and haptic walls. Specifically, larger visual cursors resulted in shorter movement times [see Fig. 7(a)]. In general, a ballistic motion is composed of an initial impulse and an error correction phases [21] and we suggest the longest movement times were observed with the smallest visual cursor because additional corrective movements were generated. To support this assertion, we calculated the maximum penetration of visual cursor into haptic wall as a measure of the haptically dominated ballistic phase—this represents the furthest participants moved. The position of the cursor at the end of a trial, represented by the absolute error for the haptic wall, represents the culmination of the error correction phase, and the difference between two variables means the magnitude of the error correction movement. As seen in Table V, a visual cursor with a diameter of 5 showed a smaller difference than with diameters of 1 and 3. In order to verify a statistical significance of the differences, an additional statistical analysis was performed. Significant differences were observed between diameters of 1 and 5 ($p = 0.038^*$), and between diameters of 3 and 5 ($p = 0.033^*$) while it was nonsignificant between diameters of 1 and 3 ($p = 1.000$). As such, we conclude that larger error correction movements led to a longer movement time with the smaller visual cursor.

Additionally, as seen in the second column of Table II, spatial discrepancy had no effect on movement time. This is likely because the initial impulse phase dominated the targeting motion. In general, participants moved the visual cursor about 80 mm during the initial impulse phase and about 1 mm during error correction phase (as shown in the fourth column of Table V). This relatively brief error correction period made the study incapable of distinguishing whether the difference spatial discrepancies impacted movement time.

Finally, there are significant interaction effects between the spatial discrepancy and the haptic wall stiffness (third column of Table III) for absolute errors for the visual and haptic walls. Specifically, the absolute error for the visual wall stayed close to constant for negative spatial discrepancies of -3.0 and -1.5 mm in the 0.4 kN/m stiffness condition whereas data from the 0.7 and 1.0 kN/m conditions increased [Fig. 9(a)]. Additionally, the absolute slope of the absolute error for the haptic wall in Fig. 9(b) increased when the haptic wall had a low stiffness. However, this metric remained constant when the haptic wall had a high stiffness. These variations indicate that the influence of (and participants' dependence on) haptic feedback during a targeting task increases when target objects have a high stiffness.

Note that an additional discussion on two absolute errors for haptic wall would be beneficial. As explained in Section III, we reported two absolute errors for the haptic wall because we excluded the 0.81% of trials in which participants did not make contact with the haptic wall. As seen in Figs. 5(b), 6(b), and 7(b), however, the experimental results show very similar values. Bias or alteration of the experimental results was not generated because this case accounted for only a small portion of the data. Consequently, we suggest that its effects on the experimental results were negligible.

It is worth discussing a number of limitations to the work and experiments described here. First, this paper considers spatial discrepancies from the perspective of how they would instantiate in a current haptic VR or AR system. Basically, it considers spatial discrepancies as deviations from a desired situation of total accuracy, or exact alignment of the visual and haptic scenes, in which the HIP is at the center of the visual cursor. However, as visual cursors typically possess graphical area (or volume) in the virtual space, this system-oriented description does not consistently match up with a purely perceptual description of the stimuli. For example, with a visual cursor of 3 mm in diameter and a spatial discrepancy (as defined in this paper) of -1.5 mm, the very edge of visual cursor will contact the surface at the moment of a haptic collision, arguably an optimal perceptual experience—see Table VI for a full set of the spatial discrepancies used from a perceptual perspective. This paper analyzes data from the system perspective and argues this is appropriate, as the primary goal of this paper is to understand the impact of system performance (in terms of alignment of visual and haptic contents) on users' experiences. As such, it is important to discuss system level variables and parameters. In the future, this paper should be complemented by studies and analysis that looks at the issue of spatial discrepancy from a purely perceptual standpoint.

Second, visual and audio cues (such as those emitted by the haptic hardware) were not blocked or obscured during the experiments and information derived from these cues may have biased or altered participants' targeting performance. To address these issues, future studies should cover or hide the PHANToM Omni and equip participants with noise-canceling headphones. However, although visual cues of the PHANToM Omni and hand were not blocked, participants needed to focus on the virtual object and visual cursor on the screen in order to complete the task. As such, visual cues from the hand and/or haptic device (situated approximately 400 mm to the side of the screen contents) were in peripheral vision. Therefore, we argue that visual cues from the PHANToM Omni and hand did not overly influence the current experimental results. Additionally, we believe the results of the study remain valid and immune to interference from extraneous audio cues. We argue this point based on data reporting that temporal asynchronies between visual and audio cues are greater than the asynchronies captured in this paper. Specifically, perceivable asynchronies between visual and audio feedback are reported to be between 70 and 125 ms [31], [32], whereas the asynchrony between visual and audio feedback generated by the haptic hardware in this paper, after conversion into the time domain, were approximately 50 ms.

Third, another limitation to the methods in this paper is that the distance between the screen and participants' eyes was not precisely controlled. However, the initial distance of about 400–500 mm was maintained during the experiments. Therefore, we argue it is unlikely to have exerted substantial effects on the experimental results. Furthermore, not controlling this variable may also improve ecological validity—in this paper, we are primarily interested in natural targeting movements, situations in which eye position may vary from motion to motion. However, we acknowledge that future studies should control, or at least measure, this variable. Finally, although not atypical for perceptually oriented studies, the relatively small number of the participants (10) in the experiment may limit the generalizability of the current findings.

V. Conclusion

This paper explored variations in user performance, primarily movement time, absolute errors for visual and haptic walls, and maximum reaction force during targeting tasks in conditions in which visual and haptic cues were spatially misaligned. A substantial study exploring this variable and the impact of three levels of haptic wall stiffness and three levels of visual cursor diameter on performance was conducted. The results revealed that, in the majority of situations, spatial discrepancies do not show performance degradations for the movement time. However, absolute errors for the visual and haptic walls show degradation. Moreover, lower stiffness levels led to larger absolute errors for the visual and haptic walls. Furthermore, visual cursors with small diameters negatively impacted movement time. Finally, the results indicated that, while both modalities were important, participants depended more on the haptic feedback than the visual feedback for precise targeting. Furthermore, this dependence on the haptic feedback increased when the target objects were stiffer. This analysis sheds light on the underlying perceptual mechanisms during visual-haptic targeting tasks.

In summary, we suggest that designers of haptic VR or AR systems should develop systems which enable targeting performance to particular levels of accuracy. The results reported in this paper can support this process by illustrating the performance that can be expected for different levels of spatial discrepancy, haptic stiffness, and visual cursor size. For example, if a virtual environment features a haptic wall stiffness of 0.7 kN/m and a visual cursor diameter of 3 mm, a spatial discrepancy of 1.5 mm could make a negative impact on the targeting performance.

Future work will attempt to expand the findings reported here. For example, formal psychophysical experiments could investigate the relative reliability of visual and haptic feedback in light of theories of multimodal synthesis [33]. Moreover, many objects in the world also move or deform in response to collisions and touches. Thus, another interesting avenue for future work is to explore the impact of spatial discrepancies in dynamic scenarios. Finally, the experimental results in virtual environment can be compared with an experiment in a real environment. It will reveal how people react to the stiffness of the wall in real and virtual environments.

References

[1] J. Jacko *et al.*, "The effects of multimodal feedback on older adults' task performance given varying levels of computer experience," *Behav. Inf. Technol.*, vol. 23, no. 4, pp. 247–264, 2004.

[2] J.-H. Lee, E. Poliakoff, and C. Spence, "The effect of multimodal feedback presented via a touch screen on the performance of older adults," in *Proc. 4th Int. Conf. Haptic Audio Interact. Design*, Dresden, Germany, Sep. 2009, pp. 128–135.

[3] B.-A. J. Menelas, L. Picinali, P. Bourdot, and B. F. G. Katz, "Non-visual identification, localization, and selection of entities of interest in a 3D environment," *J. Multimodal User Interf.*, vol. 8, no. 3, pp. 243–256, Sep. 2014.

[4] M. A. Zahariev and C. L. MacKenzie, "Grasping at 'thin air': Multimodal contact cues for reaching and grasping," *Exp. Brain Res.*, vol. 180, no. 1, pp. 69–84, Jun. 2007.

[5] R. Chaudhari, C. Schuwerk, V. Nitsch, E. Steinbach, and B. Farber, "Opening the haptic loop: Network degradation limits for haptic task performance," in *Proc. IEEE Int. Workshop Haptic Audio Vis. Environ. Games*, Hebei, China, Oct. 2011, pp. 56–61.

[6] C. Jay and R. Hubbold, "Delayed visual and haptic feedback in a reciprocal tapping task," in *Proc. World Haptics Conf.*, Pisa, Italy, Mar. 2005, pp. 655–656.

[7] J. M. Thompson, M. P. Ottensmeyer, and T. B. Sheridan, "Human factors in telesurgery: Effects of time delay and asynchrony in video and control feedback with local manipulative assistance," *Telemed. J.*, vol. 5, no. 2, pp. 129–137, Jul. 1999.

[8] C. Basdogan *et al.*, "Haptics in minimally invasive surgical simulation and training," *IEEE Comput. Graph. Appl.*, vol. 24, no. 2, pp. 56–64, Mar. 2004.

[9] F. Faure *et al.*, "SOFA: A multi-model framework for interactive physical simulation," *Soft Tissue Biomech. Model. Comput. Assist. Surg.,* vol. 11, pp. 283–321, Feb. 2012.

[10] S. Cotin, H. Delingette, and N. Ayache, "Real-time elastic deformations of soft tissues for surgery simulation," *IEEE Trans. Vis. Comput. Graph.,* vol. 5, no. 1, pp. 62–73, Jan. 1999.

[11] C. Basdogan, C.-H. Ho, and M. A. Srinivasan, "Virtual environments for medical training: Graphical and haptic simulation of laparoscopic common bile duct exploration," *IEEE/ASME Trans. Mechatron.*, vol. 6, no. 3, pp. 269–285, Sep. 2001.

[12] E. Papadopoulos, A. Tsamis, and K. Vlachos, "Development of a real-time visual and haptic environment for a haptic medical training simulator," *Artif. Life Robot.*, vol. 12, nos. 1–2, pp. 307–316, Mar. 2008.

[13] S. Rasool and A. Sourin, "Image-driven virtual simulation of arthroscopy," *Vis. Comput.*, vol. 29, no. 5, pp. 333–344, 2013.

[14] A. Widmer and Y. Hu, "Effects of the alignment between a haptic device and visual display on the perception of object softness," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*., vol. 40, no. 6, pp. 1146–1155, Nov. 2010.

[15] D. Zerbato, D. Baschirotto, D. Baschirotto, D. Botturi, and P. Fiorini, "GPU-based physical cut in interactive haptic simulations," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 6, no. 2, pp. 265–272, Mar. 2011.

[16] D. Wang, X. Zhang, Y. Zhang, and J. Xiao, "Configuration-based optimization for six degree-of-freedom haptic rendering for fine manipulation," *IEEE Trans. Haptics*, vol. 6, no. 2, pp. 167–180, Apr. 2013.

[17] R. T. Azuma, "A survey of augmented reality," *Presence, Teleoper. Virtual Environ*. vol. 6, no. 4, pp. 355–385, Aug. 1997.

[18] M. C. Lin and M. Otaduy, "Direct rendering vs. virtual coupling," in *Haptic Rendering: Foundations, Algorithms, and Applications*. Natick, MA, USA: A. K. Peters, 2008, ch. 8, sec. 3, pp. 165–167.

[19] R. Arsenault and C. Ware, "The importance of stereo and eye coupled perspective for eye-hand coordination in fish tank VR," *Presence, Teleoper. Virtual Environ*., vol. 13, no. 5, pp. 549–559, Mar. 2006.

[20] C.-G. Lee, I. Oakley, and J. Ryu, "Exploring the impact of visual-haptic registration accuracy in augmented reality," in *Proc. Euro Haptics Conf.*, Tampere, Finland, Jun. 2012, pp. 85–90.

[21] M. A. Khan *et al.*, "Inferring online and offline processing of visual feedback in target-directed movements from kinematic data," *Neurosci. Biobehav. Rev.*, vol. 30, no. 8, pp. 1106–1121, 2006.

[22] *Geomagic*. [Online]. Available: http://geomagic.com/en/products/phantom-omni/specifications/, accessed Aug. 29, 2015.

[23] M. Harders, G. Bianchi, B. Knoerlein, and G. Szekely, "Calibration, registration, and synchronization for high precision augmented reality haptics," *IEEE Trans. Vis. Comput. Graph.*, vol. 15, no. 1, pp. 138–149, Jan. 2009.

[24] Y. Rossetti, K. Koga, and T. Mano, "Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination," *Percep. Psychophy*., vol. 54, no. 3, pp. 355–364, May 1993.

[25] M. Makhsous *et al.*, "Investigation of soft-tissue stiffness alteration in denervated human tissue using an ultrasound indentation system," *J. Spinal Cord Med*., vol. 31, no. 1, pp. 88–96, 2008.

[26] J.-P. Kim and J. Ryu, "Robustly stable haptic interaction control using an energy-bounding algorithm," *Int. J. Robot. Res.*, vol. 20, no. 2, pp. 365–373, Aug. 2009.

[27] H. Z. Tan, N. I. Durlach, G. L. Beauregard, and M. A. Srinivasan, "Manual discrimination of compliance using active pinch grasp: The roles of force and work cues," *Percep. Psychophys.,* vol. 57, no. 4, pp. 495–510, Jun. 1995.

[28] K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: Introductory concepts," *IEEE Comput. Graph. Appl*., vol. 24, no. 2, pp. 24–32, Mar. 2004.

[29] *IBM*. [Online]. Available: www.ibm.com/software/analytics/spss/, accessed Aug. 29, 2015.

[30] M. H. Zadeh, D. Wang, and E. Kubica, "Perception-based lossy haptic compression considerations for velocity-based interactions," *Multimedia Syst.*, vol. 13, no. 4, pp. 275–282. Jan. 2008.

[31] D. J. Lewkowicz, "Perception of auditory-visual temporal synchrony in human infants," *J. Exp. Psychol., Human Percep. Perform*., vol. 22, no. 5, pp. 1094–1106. Oct. 1996.

[32] N. F. Dixon and L. Spitz, "The detection of auditory visual desynchrony," *Perception*, vol. 9, no. 6, pp. 719–721, 1980.

[33] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature,* vol. 415, no. 6870, pp. 429–433, Jan. 2012.

Chang-Gyu Lee received the B.S. degree in mechanical engineering from Chonnam National University, Gwangju, Korea, in 2008, and the M.S. degree in mechatronics from the Gwangju Institute of Science and Technology, Gwangju, in 2010, where he is currently pursuing the Ph.D. degree with the Department of Medical system engineering.

His current research interests include haptic control stability, haptic rendering, and human study during a haptic enabled multimodal tasks.

Ian Oakley received the joint B.S. degree (Hons.) in computing science and psychology from University of Glasgow, Glasgow, U.K., in 1998, and the Ph.D. degree in computing science from the University of Glasgow, in 2003.

He is currently an Assistant Professor with the School of Design and Human Engineering, Ulsan National Institute of Science and Technology, Ulsan, Korea. He has published over 80 of his research articles and reports. His current research interests include human–computer interaction and, specifically, multimodal, physical, tangible, and social computing.

Prof. Oakley is a member of ACM Special Interest Group on Computer-Human Interaction.

Eun-Soo Kim received the Ph.D. degree in electronics from Yonsei University, Seoul, Korea, in 1984.

He was a Visiting Professor with the Department of Electrical Engineering, California Institute of Technology, Pasadena, CA, USA. He is currently a Professor with the Department of Electronics Engineering, Kwangwoon University, Seoul, and the Director of the 3D Display Research Center and HoloDigilog Human Media Research Center. His current research interests include 3-D imaging and display, free-space holographic virtual reality, and digital holographic microscopy.

Prof. Kim served as the President of the Society of 3D Broadcasting and Imaging and the Korean Information and Communications Society from 2000 to 2011. He has been the Editor-in-Chief of 3D Research since 2010, and the General Chair of the International Meeting of Collaborative Conference on 3D and Materials Research since 2011.

Jeha Ryu (M'03) received the B.S. degree in mechatronics from Seoul National University, Seoul, Korea, in 1982, the M.S. degree in mechatronics from Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 1984, and the Ph.D. degree from the University of Iowa, Iowa City, IA, USA, in 1991.

He is currently a Professor with the Department of Mechatronics, Gwangju Institute of Science and Technology, Gwangju, Korea. He has published over 120 research articles and reports. His current research interests include haptic interaction control, haptic modeling and rendering, haptic application for various multimedia systems, and teleoperation.

Prof. Ryu is a member of American Society of Mechanical Engineers, the Korean Society of Mechanical Engineers, and the Korean Society of Automotive Engineering.