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HEMP—hand-displacement-based pseudo-haptics: A study of a force field application and a behavioural analysis

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Abstract

This paper introduces a novel pseudo-haptic approach called HEMP—*H*and-displac*EM*ent-based *P*seudo-haptics. The main idea behind HEMP is to provide haptic-like sensations by dynamically displacing the visual representation of the user's hand. This paper studies the possible application of HEMP to the simulation of force fields (FFs). The proposed hardware solution for simulating the hand displacement is based on an augmented reality configuration, the video see-through head-mounted display. A response model is proposed for controlling the hand displacement. This model adapts to the user's hand movements. It also accounts for a number of perceptual and system constraints. An experiment has been carried out to investigate the potential of the proposed technique. Subjects had to perform an FF strength comparison task and to fill in an illusion evaluation questionnaire. Comparison response results show that different FF strength levels are discriminable and the questionnaire indicates that subjects perceive flow pressure-like sensations. The analysis of arm muscular activity seems to confirm these results.

Keywords: Pseudo-haptics; Force illusion; Visuo-proprioceptive conflict

1. Introduction

Haptics has become an important modality in recent virtual reality (VR) systems. While research on haptics often concerns active haptics, an increasing number of works focus on alternative and lighter approaches such as passive haptics, pseudo-haptics and sensory substitutions. Pseudo-haptic approaches are solutions that exploit boundaries and capabilities of the human sensory system to simulate haptic information without active haptic systems. Our receptors' sensitivity and resolution are naturally limited. Since the brain is able to merge, to some extent, even conflicting sensory modalities into a statistically optimal common precept (Ernst and Banks, 2002), the user's experience can efficiently be deceived.

Within the field of pseudo-haptics, this paper introduces a novel approach called HEMP—*H*and-displac*EM*ent-based *P*seudo-haptics. The main idea behind HEMP is to provide haptic-like sensations by dynamically offsetting the visual representation of the user's hand, creating a spatial conflict between the "visual" and the "kinesthetic" or real hand. A number of questions are raised by HEMP. Among them, questions about the sensations one has in the presence of such a conflict and the user's reaction to it, or the applicability of such an approach to simulate some kind of haptic information. Far from claiming to provide answers to all these questions, this paper proposes to study HEMP through a specific possible application, i.e. the simulation of a force field (FF) sensation (HEMP–FF).

This paper proposes a combined hardware and software solution for implementing HEMP–FF. The hardware configuration is based on the video see-through head-mounted display (HMD) (Edwards et al., 1993), an

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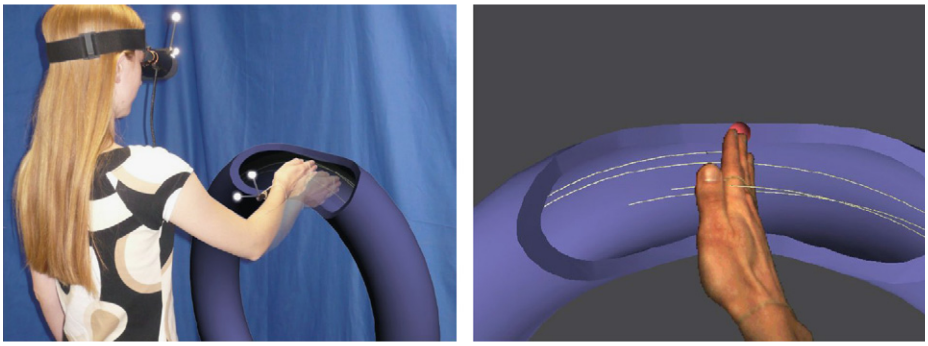


Fig. 1. Compositing of a user reaching into a virtual FF including visualised hand displacement (left), view through a video see-through head-mounted display showing the user's hand put into a force field (right).

augmented reality (AR) (Ohta and Tamura, 1999) system. Thanks to the capture of the real environment, any manipulation to its visual feedback can be performed before its actual display. It is thus the only VR configuration allowing for shifting the real hand's visual representation (not an avatar) in co-location. The hand offset is controlled by an FF illusion and a response model, which adapts to the user's hand movements. It also takes several perceptual and system constraints into account.

After a review of related work in Section 2, the paper presents the main ideas and principles of the proposed HEMP–FF solution in Section 3. Sections 4 and 5 describe the response model and some implementation aspects. Sections 6 and 7 present a user study evaluating the proposed approach from both a qualitative and a quantitative point of view. A discussion of the experimental results follows in Section 8.

2. Related work

Haptic illusions that combine present forces with manipulated visual stimuli have a long history, dating back to Charpentier's size–weight illusion (Murray et al., 1999). In this work, it was shown that subjects estimated the weights of objects with equal mass based on their apparent visual size. That is, the larger the object appeared, the lighter it was perceived.

Recent approaches follow comparable strategies of modulating given force sensations through vision. In Lécuyer et al. (2000), for instance, a stiffness feeling was simulated by linking a perturbed visual feedback with a force sensor. Similarly, it was demonstrated that a torque impression can be induced by employing a force input device combined with a virtual torsion spring (Paljic et al., 2004).

A "boundary of illusion" was identified for the simulation of haptic stiffness (Lécuyer et al., 2001). Depending on the degree of the sensory conflict, an increasing "distortion of perception" could be observed.

Pseudo-haptic feedback was applied to systems for training (Crison et al., 2004) and is used, in a less-actual force-oriented manner, in gaming interfaces and rhythm learning (Miura and Sugimoto, 2005).

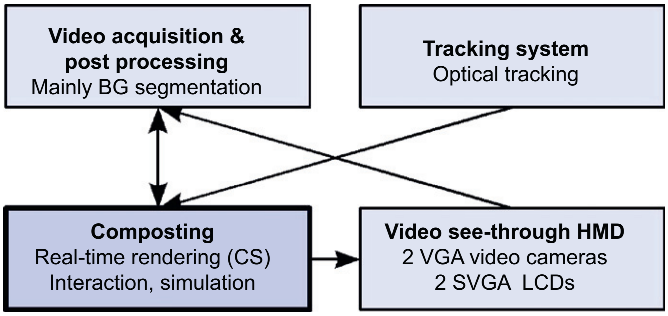


Fig. 2. System/subsystem scheme (bottom left: core system).

3. Design choices

The goal of the proposed approach is to induce the sensation of a force applied to the user's hand by visually displacing or shifting it in space. In addition to this artificial conflict between visual and proprioceptive sensory information about the user's real hand, we rely on the concept of the kinesthetic visual capture (e.g. Somers and McNally, 2003), the dominance of vision over proprioception. Exceptions for this mechanism exist (e.g. Snijders et al., 2007), but the general impact of vision on the final percept usually remains strong. Controlled by the FF illusion and response model, the visual hand is attracted and shifted along with a virtual flow visualisation. It is assumed that the user's (re-)action to this displacement might trigger the resulting force impression. We intend to provoke this sensation without any prior learning or training of the user (Fig. 1).

The system we propose for simulating the dynamic sensory conflict is based on a video see-through HMD AR setup (see Fig. 2). Thanks to this configuration, we are in the position to benefit from the advantages of acting in co-location (Paljic et al., 2002), avoiding occlusion violations and providing the real representation of the user's own hand (Perani et al., 2001; Lok et al., 2003).

The main reason for using such an AR system can be seen in its capability of providing an infrastructure for a controllable mixture of real and virtual world objects. What we actually want is to embed a manipulable real representation of the user's hand into a virtual scene. Optical see-through approaches, although capable of handling object occlusions

(Kiyokawa et al., 2000), cannot be applied. In these systems, we do not see how to induce a dynamic visuo-proprioceptive conflict, as there is no spatial control over the real hand's feedback. Video see-through HMDs (Edwards et al., 1993) are not constrained in this respect and have achieved a more mature technological level throughout the past years.

4. FF illusion and response model

The discussion of the approach is divided into two main parts:

1. *Illusion*—Theoretical basis of how the force sensation shall be induced.
2. *Response model*—Core algorithm for the FF response behaviour.

4.1. Illusion

What causes a sensation of force in our everyday life? In general, there needs to be a noticeable load applied to any of our body parts. If, for instance, one holds a book in his hand, one can "feel" its weight. Or, if one puts his hand into a streaming river, one can sense its flow pressure. In either case, the extent to which the motor system has to react to voluntarily stabilise the involved limb mainly constitutes the sensation of force.

This corrective process to maintain a desired postural stability is known as compensatory postural adjustment (CPA) (Wise and Shadmehr, 2002). That is, whenever a load impacts, it usually triggers a certain motor reaction, which then, together with other sensory cues (e.g. vision of the object, skin deformation due to surface pressure or sensory feedback of joint, muscle and tendon receptors), helps to develop a mental representation of the actual force. Conversely, the brain might interpret a given motor activity as a dedicated consequence of an event. This event is perhaps only visually observed. But it is not questioned by the observer and therefore results in a force percept.

We suppose that triggering a CPA at the hand/arm level could induce such an (illusory) sensation of force, even if there is no haptic device. This is because actual muscle work is combined with a visually manipulated feedback about the hand's location. But the artificial sensory conflict between the hand's visual and felt positions needs to be hidden, because our approach depends on visual dominance. All further details about the sensory conflict management and other important factors the FF illusion and the response model has to consider will be discussed in Section 4.2.

The following two scenarios for an interaction with the virtual FF illustrate how the force sensation is expected to occur.

4.1.1. Hand stabilisation within the FF

In this scenario, the user tries to resist a simulated force by keeping his hand at a certain position within the FF. At the moment, the visual hand involuntarily starts to move along with the flow a CPA gets triggered. In order to visually stabilise the hand, the user will most likely compensate for the displacement by unconsciously moving his real hand in the opposite direction of the flow (see Fig. 3). The actual effort of moving the real hand, combined with its almost stationary visual representation, might result in the illusion of an applied force.

4.1.2. Hand movement along with the FF

In this second scenario that adopts the already-described principles, the user moves his real-hand voluntarily along with the flow. The effect of a faster visual hand motion could be interpreted as a movement support provided by the FF. That is, the user could get the impression of an easier hand movement requiring less muscle work.

The impact of the illusion will also be influenced by the user's reliance on what the system visually feeds back. We thus intend to provide a convincing simulation, within the given constraints, mainly in terms of the FF response dynamics. Once the user has exposed his real hand to the FF, he should believe in what he sees and not question the haptic sensation he has.

4.2. Response model

The system response has to be computed in real time to guarantee a continuous interaction of the user with the virtual FF. Internally, the FF illusion and response model works as a state machine with the conditional transitions shown in Fig. 4.

At each time step, the original real-hand tracking data will be transformed according to the current system state. Some of the states (main blocks, annotated as "level"s) can be passed by, if, for instance, the performed real-hand movements are excessively fast and far. Otherwise, they are linearly interconnected and will only be parsed again, if either the visual hand re-enters the FF or if it changes its movement direction with respect to the FF. The transformed tracking data are then used for the visual repositioning of the visual hand in space.

Four main aspects contribute to the computation of effective visual hand displacement:

1. perceptual constraints,
2. FF properties,

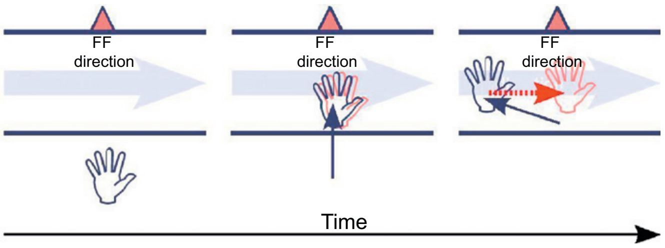


Fig. 3. Hand stabilisation within the flow (real hand: blue, visual hand: red, stabilisation area indicated by red triangle).

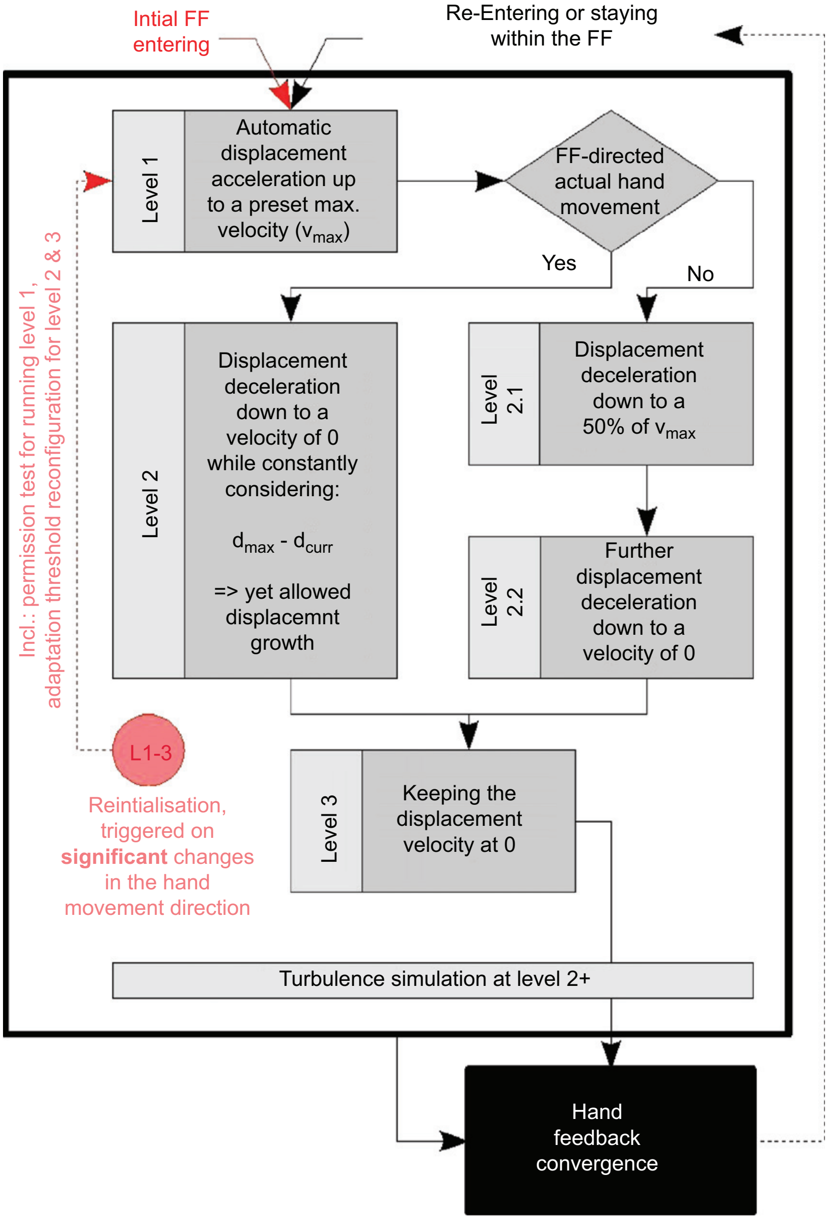


Fig. 4. Force field illusion and response model including state levels.

3. hand movement adaptation and
4. hardware constraints.

4.2.1. Perceptual constraints

This section addresses factors that could cause an undesirable break in the kinesthetic visual capture and hence in the final pseudo-haptic sensation. For instance, in Burns et al. (2005), it was found that a deviation between the real hand's virtual avatar and the user's actual pointing direction may reach about 60° before the manipulation gets noticed. In their experiment, the displacement was increased together with real-hand motions.

Since not enough is known about when a person becomes aware of a (dynamic) visuo-proprioceptive conflict, we have conducted a number of informal experiments to encircle best practice measures for displacement dynamics (e.g. the displacement velocity range: $\sim$3–8 cm/s, and the maximum displacement acceleration: $\sim$10 cm/s^2).

4.2.2. FF properties

In order to create a convincing system response, it is proposed to adapt a few basic principles for an interaction with a stream-like phenomenon.

Looking at the river example of Section 4.1, for instance, what happens (in terms of force-driven action and reaction) if someone exposes his hand to flowing water? Suppose the flow is strong enough, then the hand gets attracted and pushed to the side. Further suppose that the person wanted to hold the hand still at a certain position within the flow, then a voluntary CPA would trigger different muscles, from shoulder to forearm and hand, just to overcome the given flow pressure. Owing to visuo-motor control loops

(Wise and Shadmehr, 2002), this muscle work will result in a more or less stabilised hand. Only turbulences/swirls within the flow may provoke minor position instabilities. If the hand gets taken out of the stream, muscle pretension directed against the prior steady force would cause similar hand positioning errors like when initially putting the hand into the stream. But thanks to the readjustment processes mentioned before, the hand will again be stabilised by specific muscle activity.

As depicted in Figs. 4 and 5, level 1 of the model represents the illusion onset phase, the moment the real hand gets moved into the FF. For each FF strength level F to be simulated, there exists one onset displacement distance d_{onset} within which a related maximum displacement velocity $v_{\max}$ will be reached. That is, the visual hand will constantly be accelerated and shifted along with the flow, away from the real hand's position in space (see Figs. 3 and 5). It is expected that in a hand stabilisation scenario, the user's reaction (i.e. CPA) during this phase is the most intensive, probably the most important. The visual onset drift is meant to trigger a motor reaction, globally reflecting the actual effort to resist the induced force. d_{onset} and $v_{\max}$ can hence be understood as the first key response parameters. To support the visual capture, after the onset phase, an additional turbulence/swirl effect (small positional oscillation of the visual hand) gets activated.

A supplementary set of parameters is required for practical reasons. One can imagine that several problems would appear, if the drift velocity were kept at a certain value once the onset phase was passed. The user would need to move his real hand further into the opposite direction of the FF, just to see his visual hand stabilised at the desired position. This will not be possible for a longer time. Because at some point, due to the limited field-of-view of HMD's cameras, it will not be possible to capture the real hand anymore. Moreover, the illusion would most likely break under extreme conditions (e.g. having the user pointing straight to one side when seeing the visual hand in front of him). One opportunity to solve these issues could be to keep the user's real hand within the cameras' field-of-view by a smooth fade-out of the displacement velocity. HEMP–FF provides a hand movement adaptation mechanism that does exactly that.

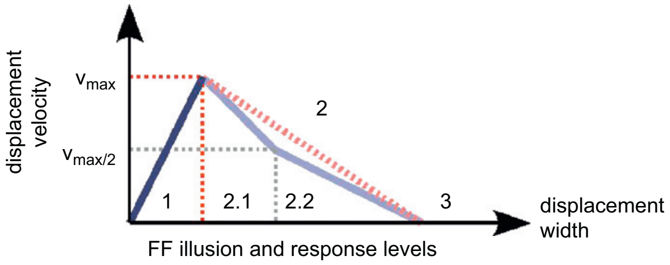


Fig. 5. Displacement velocity development with the model references and adaptation thresholds indicated.

Even if not explicitly studied in the experiment, our model is prepared to handle two further specific interaction cases. First, for a continuous sweeping through the virtual FF, the FF effect could be re-triggered up to a defined maximum displacement distance. Second, if either the displacement limit is reached or the user has taken his visual hand off the FF, then a specific treatment takes place to reduce the offset between the real hand and its visual counterpart (Burns et al., 2005). We propose to call this process "hand feedback convergence". It aims at an efficient, but well-hidden offset reduction.

4.2.3. *Hand movement adaptation*

This section describes how the system response adapts to the user's hand movements. The main reason for this adaptation comes from perceptual and technical constraints. None of the system treatments should distract the user's attention from the interaction with the FF. This also requires that the user cannot directly see any part of his real arm or hand.

The hand movement adaptation provides two different methods (see Figs. 4 and 5, levels 2, 2.1 and 2.2).

4.2.3.1. Hand movements along with the FF. If the user performs an FF-directed hand movement, then the displacement deceleration after the onset phase can be weaker (i.e. simple linear decrease as a function of the remaining displacement space). In fact, there is no "force to overcome" for the user and the displacement (more precisely, hand movement support response) could be applied for the whole time the visual hand stays within the FF. The only limits are the maximum allowed displacement distance (adaptation threshold to level 3, see Figs. 4 and 5) and the actual FF object boundaries.

4.2.3.2. Hand stabilisation and movements against the FF. The displacement velocity fade-out is originally based on a negative exponential function with the 1D-distance of the real hand from the FF entry point (along the FF axis) as a parameter. This yields a progressive, hand-movement-dependent velocity reduction reflecting the user's "work applied to the system". In a preliminary validation of the study presented in this paper, we saw that the user's sensitivity to the fade-out function shape is not very high. We chose a simplification instead. That is, the model has two major fade-out steps integrated (see Figs. 4 and 5, adaptation thresholds to levels 2.2 and 3), with the first and faster deceleration down to $v_{\max}/2$ and the second and slower deceleration down to a displacement velocity of 0. The steps' widths scale with the force to be simulated.

Level 3 of the FF illusion and response model keeps the displacement velocity at 0 until another valid (re-)trigger event appears (see Fig. 4). Validity is given as long as a sufficient displacement space remains before its maximum is reached.

When the hand movements are too small to compensate for the FF effect, the visual hand gets transported until the end of the FF and there finally stopped.

4.2.4. Hardware constraints

The response model has also to consider some hardware constraints. One of them is related to the often limited field-of-view of the cameras of current video see-through HMDs. Once the real disappears from the cameras it cannot be captured anymore and its visual counterpart also disappears. The maximum displacement distance (i.e. the maximum possible deviation of the real hand from the actual viewing axis) is thus constrained by the cameras' field-of-view.

Other drawbacks are the limited quality (e.g. in resolution and colour fastness) of displays and cameras and the often narrow field-of-view of the displays themselves.

5. Implementation details

In the current implementation, we use a lightweight embedding of the user's real hand into the virtual scene (Ortega, 2007) (see Fig. 6).

While running a distributed scene graph real-time rendering and interaction framework, the live captured and segmented real hand is applied as an RGB-alpha texture onto one invisible carrier plane object per stereo channel. Each plane is computed as a perpendicular section of the corresponding viewing frustum at head-to-hand distance. An optical tracking system (see Section 3) is used to determine position and rotation of both the user's head and his hand within a defined interaction space.

HEMP–FF manages the vertices of these carrier planes. Their final positioning (in world co-ordinates) depends on particular response or force effect stimulation conditions and on the state of the FF illusion and response model. The maximum allowed displacement width is currently set to 10 cm for an outstretched arm (i.e. at a distance of about 50 cm in front of the user). The effective horizontal hand shift has been determined to be about ±20°.

The integration of live video data into the virtual scene requires a synchronisation mechanism in order to align both contents. Video processing has been identified as the system bottleneck. To address this problem, the average latency was measured and used for temporally buffering tracking data before using it for computations. The overall display rate was 16 frames/s.

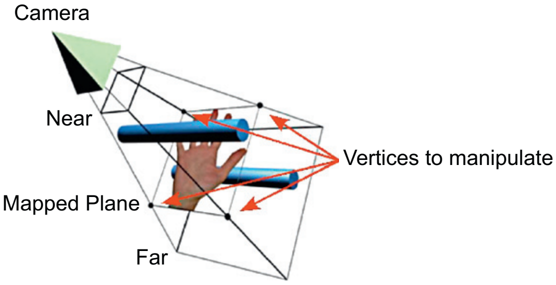


Fig. 6. Mixing approach (Ortega, 2007).

6. Experiment

The main purpose of the experiment was to study the potential of using dynamic spatial hand displacements for the visual evocation of a pseudo-haptic FF or flow pressure sensation. It was designed, first, to investigate whether there is an according force sensation and, second, whether our FF illusion and response model can generate discriminable force levels.

Subjects had to perform a forced-choice FF strength comparison task (see Section 6.3.1) and to fill in an illusion evaluation questionnaire (see Section 6.3.2).

The video see-through HMD used for the experiment (see Fig. 7) had two forward-pointing VGA cameras built-in and provided one opaque SVGA display for each eye (total field-of-view: approximately 32° horizontal and 24° vertical). It weighed approximately 250 g.

6.1. Subjects

Thirteen healthy adult volunteers (18–55 years old, four females and nine males) participated in the experiment. Ten of them were right-handed and three ambidextrous with a larger right-hand usage in their everyday life. The subjects did not know the goal of the experiment. Ten of them had never used a comparable setup. Most were even completely new to AR/VR. The rest had either attended an AR/VR class or experienced similar environments in demos. None of the participants suffered from serious vision problems (corrected vision was not considered to be problematic).

6.2. Factorial design

In the following, a comparison condition comprises two trials of reaching movements whereas a distraction

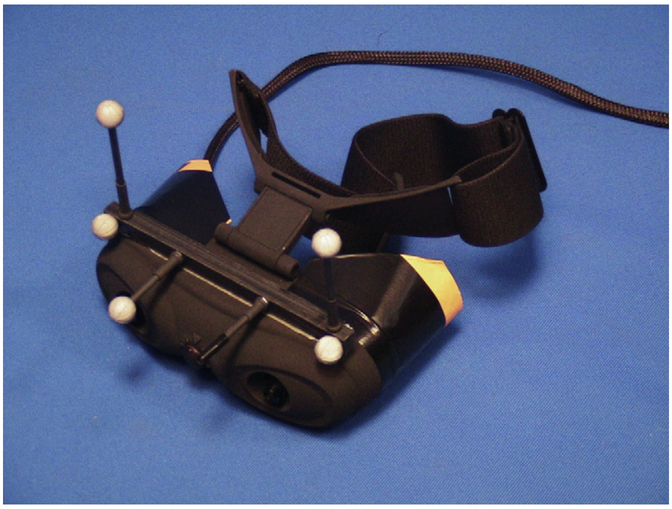


Fig. 7. Video see-though HMD used for the experiment.

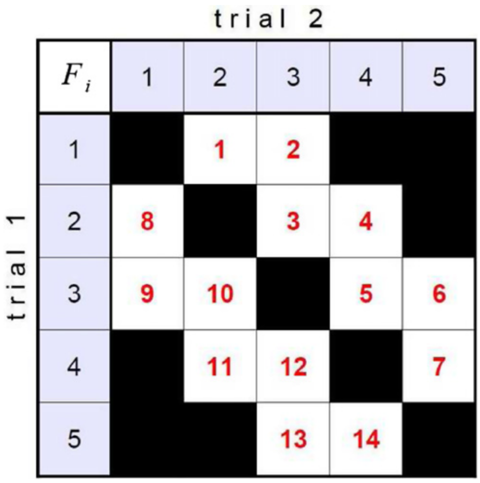
condition consists of only a single trial. As mentioned above, subjects had to perform a repetitive pairwise comparison task, with five different FF strength levels presented (F_1–F_5 with preserved relative difference, corresponding to $v_{\max} = \{3.57, 4.23, 5, 5.92, 7\}$ cm/s,). Since we chose a forced-choice protocol, all cases of equal forces were excluded, resulting in 20 instead of 25 combinations. Several informal tests revealed a high comparison performance (i.e. high success rates), when larger force differences were to be compared. We therefore reduced the set of combinations again by those exceeding a two-level difference. While considering only one FF direction (flow to the right) for the comparison, the final factorial design comprised 14 comparison conditions (C_1–C_{14}, see Table 1).

Distraction conditions (flow to the left, FF properties of F3, i.e. $v_{\max} = 5$ cm/s) were introduced to limit adaptation processes. Within a complete set of 14 comparisons, eight such distraction conditions were included, but never in between the two trials of a comparison. The comparison and distraction conditions yielded a total of 22 conditions to be equally weighted, randomly distributed and protected against effect carry-over. We employed a 22×22 random latin square for condition balancing. With 12 repetitions per condition, each participant had to complete 168 comparisons contributing to the performance analysis.

6.3. Procedure

Subjects were first asked to fill in a general information form (age, gender, handedness, prior knowledge on AR/VR, etc.). Later, the main experiment began with the comparison task (see the next section) and ended with the illusion evaluation questionnaire. The whole comparison task was divided into four parts (approximately 18–20 min each) so that subjects had some time to rest and recover.

Table 1
Condition square for the comparison task, greater force was either presented in the first trial (conditions 8–14) or in the second trial (conditions 1–7) of a comparison pair



		trial 2				
	F_i	1	2	3	4	5
trial 1	1	■	1	2	■	■
	2	8	■	3	4	■
	3	9	10	■	5	6
	4	■	11	12	■	7
	5	■	■	13	14	■

6.3.1. FF strength comparison task

Each comparison consisted of two consecutive trials of reaching movements. Initiated by an acoustic signal (beep) and starting from a rest position (see Fig. 8, left), subjects had to put their right hand into a target area located approximately 45 cm in front of them and at shoulder height. The target itself was the opened upper segment of a virtual stream tube object (see Fig. 8, bottom right). There were particles flowing through the tube, always with constant velocity. A little red sphere indicated more precisely the horizontal region of the flow to approach. The hand tracking body was fixed by rubber bands so that subjects did not need to actively hold it, for instance, by grasping (see Fig. 8, top right).

Subjects were further instructed, once they had entered the FF, to try to keep their hand within the stream, roughly at the open part's centre (red sphere). The hand stabilisation scenario was chosen for both its action clarity and its control practicability. Another beep, 6 s after the first, marked the end of a single trial (total duration: 10 s). Two such trials made up one comparison unit.

After each comparison, subjects had to identify the trial in which they found it harder to hold the hand at the desired position or they had to make a greater effort to keep/transport the hand at/towards the reaching target zone. Responses (i.e. 1: F.T1 > F.T2 or 2: F.T2 > F.T1) were registered by the experimenter.

6.3.2. Illusion evaluation questionnaire

The illusion evaluation questionnaire was given after the experiment was completed. It contained seven questions, mainly designed to obtain a first impression of the actually induced sensations and to better understand the comparison results.

Subjects were asked to describe their sensation when having the hand exposed to the visual stream and whether this sensation changed over time. They were further asked to note all differences they perceived between trials. On a seven-level scale (1–7), subjects had to indicate the extent to which the VR experience correlated with any of their real-word experiences (taken from the presence questionnaire of Witmer and Singer, 1998). This assessment had to be explained and was meant to help in situating the evoked sensation between being purely artificial and real. Finally, we asked for the cues subjects considered for their comparison judgements.

The questionnaire ended with asking for possibly perturbing factors, if any, and allowed for general remarks.

6.4. Data acquisition and analysis

The primary quantitative data basis for the analysis was the comparison responses (i.e. success rates). We grouped them in different ways to isolate particular effects,

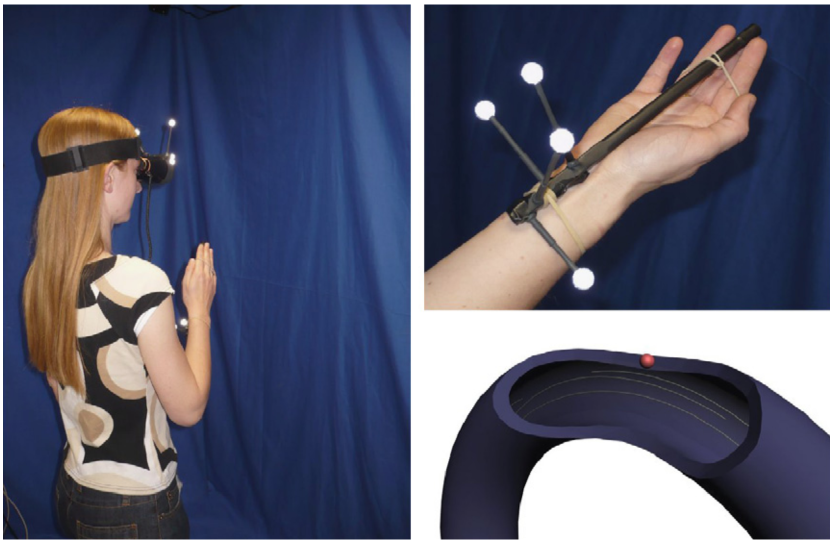


Fig. 8. Rest position (left), hand tracking body fixation (top right) and steam tube object with particle flow (bottom right).

potentials, benefits and limitations. The comparison pairs refer to the condition square (see Table 1). Groupings for the performance analysis were as follows:

1. *Overall condition ranking*—Ordered listing of all presented conditions, providing a global view of the comparison performance.
2. *Force combination differences*—Effect grouping based on the force level difference (one- or two-level difference) between the two trials of a comparison pair.
3. *Force combination zones*—Grouping based on the possible seven zones (Z_1–Z_7) for combining the existing force levels in one single comparison. With an increasing force zone ID the force levels to be compared increase, too. That is, with respect to the condition square (see Table 1), Z_1: C_1, C_8, Z_2: C_2, C_9, Z_3: C_3, C_{10}, Z_4: C_4, C_{11}, Z_5: C_5, C_{12}, Z_6: C_6, C_{13}, Z_7: C_7, C_{14}.

From the questionnaires, we obtained subjective results about subjects' conscious perception. On the comparison results, we first performed basic statistics, followed by an analysis of variance (ANOVA) with repeated measures designs, correlation tests and, if appropriate, post-hoc analyses (e.g. Bonferoni-corrected LSD).

To evaluate the subjective perception of HEMP–FF, the analyses of the behavioural data focused on the effects of the FF levels on subjects' motor responses. The hand shift began and triggered motor adaptation once the visual hand was introduced in the visual particle flow and had to be kept stabilised on reaching the target (i.e. hand reference position to control despite visual hand shift perturbations). The dependent variables analysed are the hand kinematics, the corresponding muscular activity of the arm adduction muscle (musculus pectoralis major) and the lateral balance activity associated with the reaching when the hand is within the FF.

For each trial, tracking data of the subject's head and hand were recorded at 60 Hz. Arm adductor activity was recorded at 1000 Hz using a surface electromyographic system. Balance data were obtained from a force plate sampled at 1000 Hz. A visual inspection of behavioural data before statistical analysis allowed verifying the homogeneity and validity of the behavioural measures. The behavioural variables were analysed for the different FF levels using the one-way ANOVA method.

7. Results

The results will be presented according to the condition grouping. We had to exclude a few comparisons from the analysis in which subjects were not able to give any comparison response (data loss rate: 2.24%). Responses were not given, for instance, in cases of strong uncertainties or if subjects reported a lack of concentration on the task.

7.1. Overall condition ranking

In Table 2, all conditions are shown, ordered by their response success rate (mean and standard deviation, SD). The related main variables (force combination differences and zones) are indicated as well. Their particular impact on the results will be presented in the following sections.

7.2. Force combination differences

In our experiment, only one- and two-level differences were presented. The comparison performance found for two-level differences (mean: .818, SD: .068, $v_{\max}$ ratio: 1.4) was significantly better ($F(1, 12) = 49.72$; $p < .0001$) than for one-level differences (mean: .68, SD: .088, $v_{\max}$ ratio: 1.18). Fig. 9 shows these results. In order to determine whether the value for one-level differences was dissimilar from chance, we compared it to a hypothetical 50% success score. A separate variance estimate *t*-test was employed,

Table 2
Condition ranking and overall results

Rank	1	2	3	4	5	6	7	8	9	10	11	12	12	14
Cond.	6	4	2	13	7	9	5	11	3	10	14	12	1	8
Diff.	2	2	2	2	1	2	1	2	1	1	1	1	1	1
Zone	6	4	2	6	7	2	5	4	3	3	7	5	1	1
Mean	.883	.863	.837	.830	.814	.760	.759	.734	.723	.689	.640	.639	.628	.540
SD	.113	.110	.159	.128	.141	.156	.208	.167	.164	.218	.190	.194	.126	.195

Each rank shows the condition with respect to the condition square (cond.), the condition-dependent force level difference (diff.) and zone as well as the related mean success rate and SD.

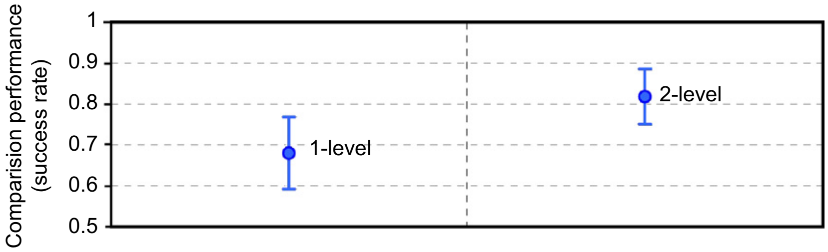


Fig. 9. Influence of the force combination differences on comparison performance (means and SDs).

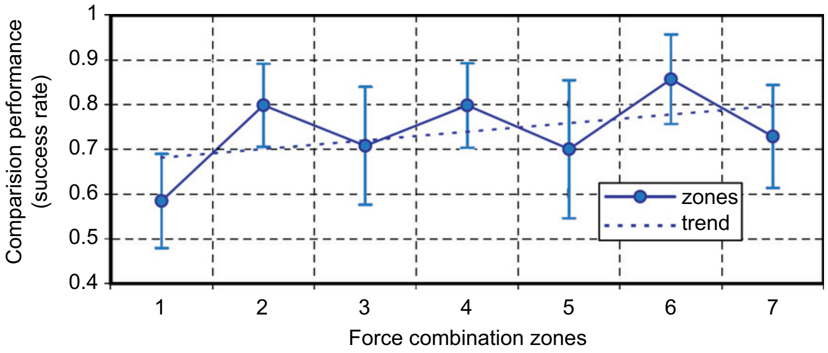


Fig. 10. Influence of the force combination zones on comparison performance (means and SDs).

which actually revealed a significant difference from chance ($t = 7.369$; two-sided $p < .0001$).

7.3. Force combination zones

This last grouping is based on the seven force combination zones described in Section 6.4. Due to the results shown in Section 7.2 and that the force combination differences are inherently coded in the force combination zones, the found effect on the comparison performance could be expected ($F(6, 72) = 10.89$; $p < .0001$). To analyse whether subjects' performance correlated with the presented force combination zones, we applied Pearson's product moment correlation test. A positive correlation was found ($r^2 = .079$; $p < .008$, see also the trend curve in Fig. 10).

7.4. Illusion evaluation questionnaire

The purpose of the illusion evaluation questionnaire was to isolate subjects' conscious sensations, yield a score on how close the experience was to real-world experiences and identify possibly perturbing or confusing factors.

Concerning their sensations, almost 70% (9 out of 13) of the subjects reported, for instance, "a force that you were obliged to stem against with your hand", "a flow more or less strong as water", "a force that obliged me to compensate with my muscles", "a pressure exerted by the flow, tearing the hand away", "felt that the flow was pushing my arm", "got the hand pushed to the side, requiring (muscle) tension to resist" and "the flow seemed to push my hand away" or similar statements. Seldom, subjects noted that the sensation diminished over time. Most either did not perceive or did not remark any change.

The consistency of the VR experience with something that was experienced in the real world was rated with 4.54 out of 7 (SD = 1.14). Subjects explained their sensations, for instance, as "a driving force", "water stream", "air stream as perceived when holding the hand outside of the window of a driving car", "air blowing on my hand", "holding the hand into some stream", "putting the hand […] under an air head-dryer" and "the sensation was very real". But there were also statements like "only few situations in which we see our hand going away and need to apply a specific force to control it", "no tactile sensation" or "feeling as if I would have lost my 'tactile' sensation".

The strategies to come to a comparison judgement seemed to differ among the subjects. We could separate two groups, of which the first relied more on their sensations, i.e. "by the feeling of how much I had to force my hand", "by the feeling of heaviness", "by muscle contraction and the contraction duration", "by the first moment of the force impact", "by the resistance I had to oppose", "by how much effort I had to put", "I just 'felt' the strongest flow" or "whether I felt my pectoral muscle fatiguing". The second group based its judgements mainly on observations of the scene and/or their own actions, as "by the position and the movement of the hand", "by the displacement of the hand before my reaction", "by how far I pushed my hand to the left", "in the strongest I saw my hand shifted more" or "the more separated from the centre it was, the more force I had to do to get it (the hand, author's note) back".

The duration of the experiment and the ergonomics of the see-through HMD were partially remarked as slightly unpleasant.

7.5. Quantitative evaluation of HEMP–FF

The aim of the quantitative analysis of the behavioural data is, first, to question the functional effect of the FF illusion on the motor response by describing the adaptive hand movement, the arm muscular activity and the balance adjustments. Second, the relation between subjects' answers in the evaluation questionnaire and subject perception to the FF illusion is to be verified.

7.5.1. Hand kinematics analysis

The kinematics analysis of the FF-dependent adaptive hand motor reaction shows that subjects followed the experimental instructions. Since the moment the visual hand was displayed inside the flow, they reacted to the FF effect by an on-line correction of the hand position.

Once the hand was introduced in the visual FF (i.e. instantaneous shift of the visual hand from the left to right), all subjects behaved in the same way, triggering a fast lateral hand displacement in the opposite direction to compensate for the visual hand displacement (see Fig. 11).

The amplitude of the reactive hand movement increased proportionally with the FF level ($F(4,48) = 683.13$; $p < .0001$). As a consequence of the FF-dependent arm reaction correlated to the visual hand shift, the hand displacement and its duration, from the flow entering to the stabilisation position (i.e. visual hand at the target location and real hand still standing), increased with the FF level, too (see Fig. 11).

While moving the visual hand towards the target, the arm compensatory strategy was to maintain an accurate and stabilised hand position. The target was considered as the visuo-spatial reference for the on-line guidance of the visual hand.

Even if this result was expected as a basic compensation of the positional shift of the visual hand, this adaptive behaviour indicates that the experimental task based on the FF illusion and response model triggered an efficient hand position control to maintain an accurate guidance toward the reaching target.

7.5.2. Arm and hand muscles activity analysis

The analysis of the arm electromyographic activity associated with the FF compensation behaviour focused on the right major pectoralis muscle. Its main adductor role at shoulder level is to move the arm laterally (from right to left) relative to the sagittal plane of the body. The analysis shows that the average activity of the arm adductor muscle when the hand is in the virtual FF

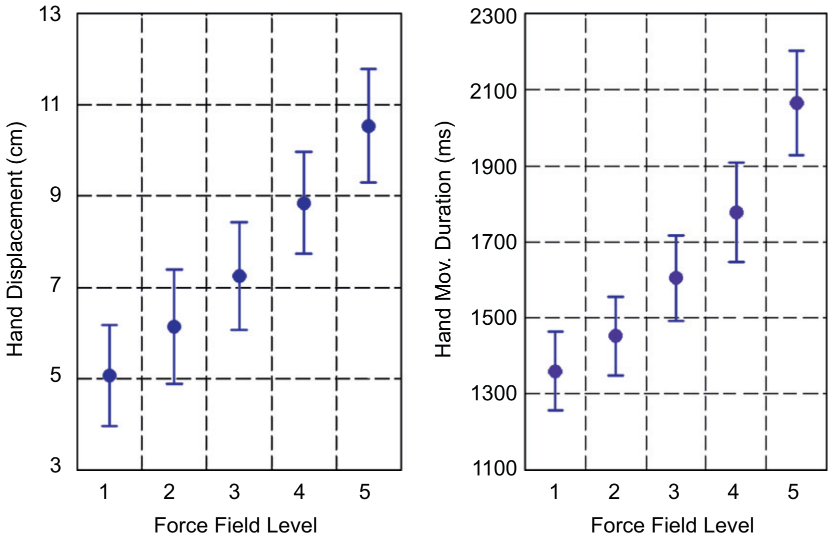


Fig. 11. Means and SDs of the hand displacement (left frame) and corresponding hand movement duration (right frame), compared with the different force field levels.

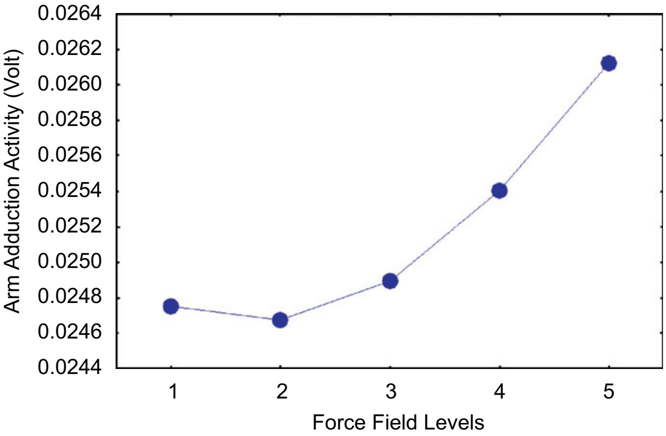


Fig. 12. Electromyographic activity of the right arm adductor muscle (musculus pectoralis major) for each level of visual force field.

increased significantly with the FF level ($F(4,48) = 6.25$; $p < .0004$, see Fig. 12).

It is interesting to note that at the hand level, there is no significant effect of the FF level on the hand (or wrist) flexor muscles ($F(4,48) = 1.47$; $p > .2$). This result indicates that the corrective hand positioning during the compensation was mainly taken into account by the shoulder muscle system. The wrist control was not significantly involved in the correction of the hand position.

7.5.3. Balance control analysis

The analysis of the lateral displacement of the feet centre of pressure (i.e. along the Z-axis parallel to the FF orientation) when the visual hand was stabilised on the target shows that there is no significant effect of FF levels on the overall body oscillation ($F(4,48) = 1.33$; $p > .2$). This postural invariance, in spite of hand kinematics and neuromuscular adaptation to the FF levels, could be considered as a global indicator of a conservative postural behaviour unaffected by HEMP–FF.

8. Discussion of the experiment

The goal of the experiment was to investigate the potential of our hand-displacement-based pseudo-haptic FF approach. Important measures were the user's sensation when he exposed his hand to the virtual FF and the system's capability to evoke a number of discriminable force or flow pressure levels.

To answer to the first question whether there is any sensation of force, the statements made in the illusion evaluation questionnaire appear to be promising pointers. Close to 70% of the subjects felt as if their hand was “pushed” by the flow or as if a force was “exerted” on their hand. The reported comparison judgement strategies support these subjective impressions. The virtual-to-real-world experience consistency score (4.54 out of 7) we have obtained from the illusion evaluation questionnaire suggests a light tendency towards a more realistic than a purely artificial sensation. However, we have to note that the experimental procedure could have influenced the answers to the questionnaire. We thus need to conduct further evaluations in order to confirm the subjective results.

Regarding the second question about the evocation of different pseudo-haptic force levels, the proposed FF illusion and response model seem to be able to provide the user with the required distinguishable sensory information. For the two main aspects we have analysed, the highest mean scores were found: for two-level differences (81.8% vs. 68% for one-level difference) between the trials to be compared, suggesting that greater force level differences would perform even better, and for greater force levels involved in a comparison (max: 85.7%).

As the overall condition ranking shows, there is a remarkable gap in the comparison performance (min: 54%, max: 88.3%). This might partially be due to system constraints, but also to what we know about cases of limited precision in the proprioceptive sensory system (Scheidt et al., 2005). Lower scores were most often found when smaller hand motion differences or slower hand movements in general were provoked.

Concerning the question about the functional effect of HEMP–FF on adaptive motor behaviour, data on hand kinematics and the arm muscular activity clearly indicate that the different pseudo-haptic force levels are taken into account by the hand sensorimotor control system. The reactive movement of the hand becomes adapted to the levels of the unreal force that perturbs the ongoing hand movement. It is important to remind that the adaptive muscular activity at the arm level is processed without any real force or mechanical constraints applied to the hand. In addition to the conscious perception of an FF during the target reaching reported by the majority of the subjects, the adaptive arm muscular responses demonstrate the real effect on the perception of the hand shift and consequently on the intentional hand guidance processes.

The illusion of an FF made that the displacement of the visual hand was integrated in the perception of the own action. Then, the visuo-proprioceptive conflict has generated, as expected, automatic sensorimotor adaptive responses. This shows that the functional perception of the own action could be artificially biased to generate adapted visuo-manual behaviour for 3D interaction in mixed visual and motor space.

At the balance level, the lack of an FF effect on upright postural adjustment despite the hand adaptive control during the task is interesting. This postural stability could be due to the absence of adaptive balance responses, the FF having no sensory or motor influence on the control processes of the upright standing, because of the lack of real mechanical or physical constraints. On the conrary, the standing stability could also be a sign for triggering a whole-body stabilisation strategy, which reduces postural oscillations for an optimal control of FF-dependent hand corrections. Further analysis would clarify this point.

Taken together, the qualitative and quantitative behavioural results have to be considered as a preliminary descriptive knowledge about the way the perception–action loop interacts within the 3D space when an illusory force is applied to the active hand. Force perception considered together with the hand reactive behaviour also confirm the ergonomics of the FF illusion already demonstrated by the subjects answers about their conscious perception of something that is however just an illusion. Consequently, the qualitative and quantitative data validate the response model proposed in this study and prove its objective interest for 3D interactive contexts.

9. Conclusion and future work

This paper introduces the HEMP technique, a novel pseudo-haptic approach based on an artificial visual displacement of the user's hand in space. This technique has been studied through an FF simulation application. A combined hardware and software solution has been proposed.

An experiment was conducted to evaluate the FF simulation system. Subjects were able to discriminate the proposed FF levels. The analysis of the questionnaire shows that most participants feel a "stream-like" or "pushing" force sensation. This force illusion seems to be confirmed by the analysis of the arm muscular activity.

Despite these promising results, there are still a number of aspects to investigate. Future work includes research in several directions. First, theoretical studies for gaining a deeper understanding of the involved sensorimotor integration processes would be important. The proposed technique would also benefit from technological improvements, because some of the observed limitations were probably caused by the low-fidelity setup used for this study. The HMD, and in particular the video see-though HMD technology, is rapidly evolving. Thus, more comfortable systems with better characteristics (e.g. camera and display resolution, field-of-view, processing lags) should improve both the sensations and the effective force level quantity and range. The FF illusion and response model would need to be revised according to the results of the theoretical studies and an improved setup. Then, more user studies would be necessary to assess HEMP–FF in more detail and to identify its limitations. These studies should aim at performance (e.g. quality of the sensation, number of discriminable force levels) and ergonomics issues.

Finally, usability and practicability of HEMP–FF in actual applications will have to be considered. Possible applications are the exploration of scientific data or the development of sensible interfaces. Other interesting fields for applications may be education and entertainment, scenarios in which flows of different intensities or even different matters could be experienced without having them "really present". Beyond the HEMP–FF technique, other HEMP approaches like touching virtual surfaces or lifting virtual objects need to be investigated. The research perspectives and associated developments could now take advantage of HEMP–FF to reach more direct perceptual processes that could provide access to more intuitive adaptive behaviour for optimised 3D interaction.

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Appendix A

1. Please describe your sensation when exposing your hand to the visual flow.
2. If the sensation has changed over time, in WHICH way/HOW did it change?
3. If you have perceived differences between the trials, HOW MANY and WHICH differences did you perceive? Please describe each difference.
4. How much did your experiences in the virtual environment seem consistent with your real-world experiences? (1: inconsistent ⇒ 7: consistent; give an explanation of the score):

1	2	3	4	5	6	7

5. In case you felt confused or disoriented at some point during the experiment, WHEN, HOW STRONG and WHY did this happen?
6. General remarks.

(Question 7 is presented on an extra sheet after all other questions had been answered):

7. Please describe the indicator(s) you used to determine which of the two consecutive trials to compare was actually the "stronger" one.

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