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Supplementary Materials for

The uncanny valley of haptics

Christopher C. Berger, Mar Gonzalez-Franco,* Eyal Ofek, Ken Hinckley

*Corresponding author. Email: margon@microsoft.com

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Other Supplementary Material for this manuscript includes the following:
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Materials and Methods

In the present research we ran several experiments to better understand the dynamics of the haptic perception, and examined when and how the aforementioned uncanny valley is elicited, and perhaps more importantly, can be avoided. We hypothesize that the context in which the haptics are provided may be just as important as the increased characteristics of the haptics. In fact, the experience may worsen if there is a mismatch between improved haptic quality and the increased expectations. Such a finding would be consistent with the existence of an uncanny valley of haptics. Previous work has found that the uncanny valley can be shifted or eliminated by manipulating various aspects of the simulations, for example using cartoonish features to reduce the mismatch between its human-likeness and the perceived realism (*8*, *10*). We transfer this idea to haptic stimulation and rely on the brain's ability to process and integrate perceptual information from our senses (bottom-up) while taking into account higher cognitive processes (top-down) (*3*, *9*, *11*). It is known that cognitive factors, such as the semantic relatedness of stimuli (unity assumption rule) or the content of one's imagination will affect how the brain integrates information from our different senses (*12*, *13*). In normal perception, top-down influences can determine what and how we perceive in our environment, in VR, this can make the difference between a totally realistic experience and a broken illusion (*6*). To test the hypothesis that the uncanny valley both exists and can be manipulated, we ran three experiments:

Passive Experiment: In the main experiment, we aim at eliciting an Uncanny Valley of Haptics that would validate our theory. During the stimulation phase inside VR participants (n=27) placed a virtual stick (which they held using the handheld controllers) in a marked area — that takes the form of a cylindrical smoke cloud (Fig. 1D), the design of the cylinder with transparencies allow the participant to continue seeing the stick, as opposed to a black box. As the stick enters the marked area participants automatically received the haptic feedback without having to move, hence the naming: passive experiment.

Dynamic Experiment: In this experiment we aimed at exploring if active motion could help avoid the Uncanny Valley. Inside VR, participants (n=9) held the same stick as in the Passive Experiment, with the handheld controllers, however in this case they received the haptic experience only when they moved the stick up and down in a repetitive manner. The cylinder was therefore not present and for every movement there was one haptic trigger. Hence an action-reaction paradigm is enabled.

Causal Experiment: In this experiment we explored the power of top-down predictions to reduce the Uncanny Valley effects. Inside VR, participants (n=8) placed the stick in the marked area in the same fashion as the Passive experiment setup. Similarly, they automatically received the haptic feedback without having to move further. However, in this experiment the marked area was dynamically rotating, giving the impression of randomness, which could be a possible reason for enhanced haptics.

In all three experiments, we rendered four different haptic conditions, ranging from:

No Haptics: No haptics are rendered. Participants are asked to grab the two hand held controllers as if they were holding a stick. They move the stick forward to introduce it to the marked area. However, in this condition, no haptic feedback is provided.

Generic Haptics: In this condition, when the virtual stick is placed inside the marked area, a generic vibrotactile buzzing is delivered at both controllers equally and in an intermittent pace —vibrotactile stimulus was 80 ms, with the inter-stimulus interval set at 500 ms (Fig. 1C).

Spatialized: A funneling rendering. In this condition, when the virtual stick is placed inside the marked area, different vibrotactile amplitudes are delivered at each controller. Thus, generating spatialized touch sensations. Again, vibrotactile stimulus is delivered synchronously on both controllers for 80 ms, with the inter-stimulus interval set at 500 ms (Fig. 1C).

Visual+Spatialized: A visually dominated funneling rendering. In this condition, the Spatialized stimulation is replicated, only this time a white marble appears at the positions where each spatialized touch is delivered (Fig. 1C).

Participants in each experiment underwent all of these conditions for a 30 seconds each (experiencing 50 haptic trials per condition in a within subjects design). At the end of each condition participants completed the standard IPQ presence questionnaire (*7*, *14*) and responding to additional questions on the realism of the touch sensations (see Table S2). We then explore the correlations and loading factors for all questions in order to aggregate them into a single score using well stablished Principal Component Analysis (PCA), and Factor analysis (*15*).

During the experiments participants wore a Head Mounted Display (HMD), and sat on a chair while holding one touch controller with each hand (Fig. 1D). They were then shown an avatar in first person perspective, which they could control as if were their body: The avatar held a stick between its hands (Fig. 1D). Participants were told to move the stick in different ways depending on the condition.

Participants

A total of 44 participants were recruited. They were healthy, reported no history of psychiatric illness or neurological disorder, and reported no impairments of touch or vision (or had corrected-to-normal vision). The experimental protocol for each experiment lasted for 15 minutes, was approved by Microsoft Research, and followed the ethical guidelines of the Declaration of Helsinki. Participants gave written informed consent and received monetary compensation in exchange for their participation.

To make sure that participants were not influenced by the order of the conditions, the expositions were randomized across participants.

Apparatus

All visual stimuli were presented via an Oculus Rift HMD equipped with the integrated 'Constellation' positional tracking system. The tracking system is enabled by stationary reference units that use optical IR LEDs and inertial sensors to track the user's head and handheld controllers. The Oculus Rift uses a Pentile OLED display with a 1080x1200 resolution per eye and a refresh rate of 90 Hz. The effective field of view (FOV) for the participants is of 110 degrees.

Participants received vibrotactile stimuli delivered simultaneously from two independent handheld Oculus Rift controllers while inside the virtual environment (see Fig. 1D). The vibrators were set at the desired amplitude and duration using custom scripts in C# and implemented in Unity 3D Software (version 2017.1.0f3). A linear modulation of the amplitude of the controllers was used to elicit the illusion that the location of the vibration was at various points between the users' hand. This was done in accordance with previous research on the funneling illusion of touch, that has shown the brain interpolates two synchronous vibrations in different hands as one when they are holding an object (*4*).

Questionnaire

In all three experiments, participants were asked to fill out a questionnaire that probed their experiences while in the virtual environment. The questionnaire consisted of a series of statements about one's experience within the virtual environment, one's awareness about the external environment, and about how the vibrations were felt during the haptics conditions of the experiment (Table S1).

The questions Q1 to Q8 were included from the Igroup Presence Questionnaire (IPQ) (*7*), while questions Q9 to Q12 were addressing the sense of touch generated during the stimulation. Participants ranked the newly created questions in a scale from (-3 fully disagree) to (3 fully agree).

Analysis

In order to analyze the questionnaire, we conducted a Principal Component Analysis (PCA) on the 12-items to detect the main factors explored by the questionnaire (*20*). PCA analysis is particularly recommended for questionnaires that try to measure only one or two single factors. In these scenarios, some of the questions are more relevant than others, i.e. have greater variability among participants, while other questions might be non descriptive of the experience. However, the important questions might be hidden when using a regular average of scores by the rest of the questions. PCA allows to objectively calculate the loadings for the most relevant questions, this way questionnaire responses can be analyzed in a more meaningful way (*15*).

The main factors that the PCA discovers in the questionnaire are selected using the Kaiser criterion (*15*). We first calculated the correlation matrix between all the questions to see if any question was rendered insignificant (excessive large correlation coefficients), and hence would need to be removed. Additionally, we looked at the whole questionnaire to find if some questions were too unrelated to the rest of questions (very low correlations). In order to guaranty the accuracy of this factor selection process we calculated the determinant of the matrix. Typically, a determinant smaller that 0.0001 is consider problematic.

At the end, the PCA provides a set of loading for each selected factor, these loadings are weights that give different importance to different questions, maximizing the most relevant ones for each factor (*15*). In particular we used PCA oblique rotation, since we expected factors to be also somewhat correlated in this questionnaire (all questions were more or less addressing similar effects).

Following the PCA analysis, we attempted to fit a curve to the loading from each condition for each factor from the PCA using a linear model, a quadratic function, and a polynomial function.

Planned comparisons between the different conditions in each experiment were carried out using non-parametric Wilcoxon signed-rank tests, to avoid issues typical of non-continuous data, when tackling within-subjects data the Wilcoxon test was paired.

PCA Results

We find that the determinant of the correlation matrix (det= 0.011) indicated that all the questions correlated reasonably well with all others and none of the correlation coefficients are excessively large. So, we didn't need to remove any questions at this stage.

The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis KMO = .83 (*15*), and all the KMO values for individual items were above the acceptable limit of 0.5. Bartlett's test of sphericity, χ^2 (66)=216, $p<0.001$, indicated that correlations between items were sufficiently large for PCA. An initial analysis was run to obtain eigenvalues for each component in the data. Two components had eigenvalues over Kaiser's criterion of 1 and in combination explained 53% of the variance. The scree plot inflexion also confirmed retaining only two components. The model fit for the two components matrix was 0.94 (greater than the recommended 0.90).

Table S1. Questionnaire and factor loadings. Main Variables of PCA.

Questions / Factor Loadings	Factor 1	Factor 2
Q1: How aware were you of the real world surrounding while interacting in the virtual world? (i.e. sounds, room temperature, other people etc).	0.610	
Q2: How real did the virtual stick seem to you?	0.507	
Q3: I had a sense of acting in the virtual space, rather than operating something from outside.	0.714	
Q4: I did not feel present in the virtual space.	0.643	
Q5: I was not aware of my real environment.	0.816	
Q6: In the Virtual reality world, I had a sense of "being there".	0.803	0.111
Q7: I felt present in the virtual space.	0.786	
Q8: I still paid attention to the real environment.	-0.711	
Q9: I felt as if the vibrations came from the virtual stick.		0.821
Q10: I felt as if the vibrations came from multiple locations between the virtual hands.		0.602
Q11: The vibrations seemed to originate from a single location at a time.		0.820
Q12: I could locate where the vibration originated on the stick.		0.794
Eigenvalues **% Variance** **Inter-factor correlation**	4.00 33.4% 0.33	2.37 19.8% 0.53

When we apply these loadings to the factors we can calculate the subjective experience (factor 1, factor 2) that participants reported in the different conditions and experiments (Fig. 1). This process followed standard PCA questionnaire analysis methodology (*20*).

Results

In order to validate the theoretical model of Uncanny Valley (Fig. 1A) we look at the main experiment results (Fig. 1B, black solid line).

Paired comparisons directly on the IPQ questionnaire scores (Table S1, factor 1) across all four conditions (**no haptics**, **generic haptics**, **spatialized** and **visual+spatialized**) confirmed that the uncanny valley existed for the increased haptic experience (Table 2, Fig. 1B, black solid line). The spatialized condition systematically produced lower IPQ scores (Fig.1) than the rest of the conditions, despite in principle it provided an enhanced experience. However, when the funneling haptics were accompanied by a visual event (**visual+spatialized**) the score was at its highest.

Table S2. Main experiment (passive) results. Wilcoxon signed rank paired-test between conditions, as seen in Fig. 1B.

Condition / Condition	**Generic Haptics**	**Spatialized**	**Visual+Spatialized**
No Haptics	p=0.5, Z=-0.67	**p=0.004, Z=2.81**	**p=0.017, Z=-2.35**
Generic Haptics		**p=0.04, Z=-2**	**p=0.027, Z=2.2**
Spatialized			**p=0.0002, Z=-3.65**

We also ran the two additional experiments (dynamic and causal) willing to explore ways to avoid the aforementioned Uncanny Valley of Haptics. A part of the already found multimodal effect, in which a visuo-haptic combination was able to increase the perceived experience, the same haptic conditions are delivered while participants were either actively moving the controllers (**dynamic**) or when they are meet by a reason that explains the **causality** of the haptic experience. When causality is introduced as the source of the haptic experience (as a top-down source), the brain is given a plausible reason for the incremental haptic quality. We hypothesized that both active motor actions as well as more complex causal inferences could act as uncanny valley suppressors. In particular, we no longer find a significant uncanny valley of haptics in the dynamic experience (n=9) (Fig.1B, red dotted line, paired comparisons across conditions $p>.05$). When we introduce causality to the equation we find even further recovery (Fig.1B, green dotted line), while in the main experiment (passive) the valley occurs during the spatialized haptic stimulation (Fig. 1B). The same spatialized haptic experience in the causal experiment (n=8) delivers higher IPQ scores than the generic buzzing (p=0.03, Z=-2.1).

Haptic Validation

The theoretical model is based on the assumption that the spatial haptics through funneling is indeed an improvement from generic haptics (Fig. 1B). To validate this assumption, all participants were asked to report their touch perception. Indeed, the *touch spatialization* (factor 2 derived from the questionnaire, see Table S1, Fig. S1) was significantly higher for the spatial haptics conditions (**spatial** and **visual+spatialized**) than for the **generic haptic** condition (Wilcoxon paired test $p<0.001$, $Z>2.5$). The difference in perceived touch of the two spatial haptic conditions was also significant (p=0.012, Z=-2.5), despite both conditions (**spatial** and **visual+spatialized**) implemented exactly the same haptic funneling effect (see Fig. 1C).

Additionally, we further tested funneling spatialization across 10 additional participants who were asked to report the estimated touch location between the hands by pointing at the perceived location after each haptic trigger. Each participant in this additional test completed 30 trials per condition (**spatialized**, **visual+spatialized**, as shown in Fig. S1). A strong correlation between the stimuli location and the estimated location was found both when the haptic stimuli was accompanied by the visual event as well as when it was only haptic (corr=0.96, $p<0.001$, df=98, t=34.4).

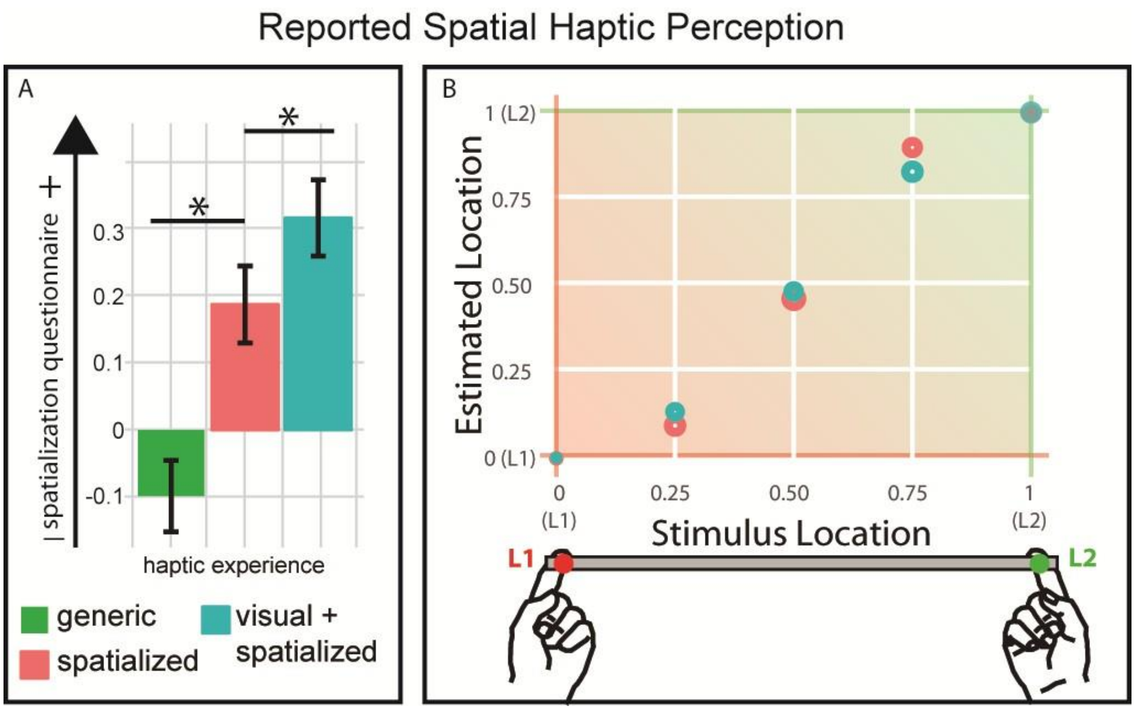

Fig. S1. Reported spatial haptic perception. Different haptic experiences enable participants to feel enhanced touch spatialization. **A**: Both the **spatialized** and the **visual+spatialized** conditions essentially produce improved tactile experience when compared to the **generic haptics** as shown by the scores on the spatialization questionnaire (factor 2). **B**: Participants were able to estimate the location of the stimuli during the spatialized haptics with high accuracy with and without the visual cues (white marble).

These results validate the improved haptics delivered by the funneling, and also are aligned with multisensory theories that show increased perception of one modality (e.g. touch) when presented together with a second modality (e.g. vision) (*3*, *9*).

Table S3. Summary of learnings and recommendations from the uncanny valley of haptics.

(i)	In haptics, overindexing in quality elicits rejection. The feedback must be commensurate with the kind of haptic stimulation provided.
(ii)	Matching with other external stimuli should prevail over precision. To overcome prediction errors and perceived inconsistencies, the richness of the haptic feedback and the other modalities must be aligned. For example, if visuo-haptic coherence is not met, the haptics, no matter how precise, can hinder the overall user experience.
(iii)	Agency over the haptics shifts revulsion. Providing agency over the haptic feedback—i.e., actively triggering the actions—can avoid haptic rejection by providing a causal explanation.
(iv)	For every enhanced haptic, there must be a reason why it occurs. Causality rules the interpretation of haptics because the brain performs powerful sensory suppression and augmentation on demand. Top-down expectations can eliminate haptic rejections.