The uncanny valley of haptics

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

During teleoperation and virtual reality experiences, enhanced haptic feedback incongruent with other sensory cues can reduce subjective realism, producing an uncanny valley of haptics.

In the field of humanoid robotics, most people are familiar with the notion of an “uncanny valley” (1): the phenomenon whereby increasing the realism of a robot—its human-like appearance or movements—yields feelings of unease, or even revulsion, in people as its representation becomes more and more (but never quite fully) human-like.

We took this notion one step further by examining whether an uncanny valley also exists for human perception of forces (i.e., tactile sensations) that might be rendered during human-robot interaction, teleoperation, or other virtual manipulation tasks in virtual environments (2). That is, do enhancements of the “actual” forces applied by robots (or other devices) necessarily lead to an improved subjective experience by the human operator?

We argue that the answer is no: The subjective perception of haptic sensations by a human operator critically depends on the fusion of haptic and visual stimuli as a unitary percept in the human brain (3). If the fidelity of the haptic sensation increases but is not rendered in concordance with other sensory feedback (such as visual and auditory cues), the subjective impression of realism actually gets worse, not better. We refer to this degradation as the uncanny valley of haptics (Fig. 1A).

To demonstrate this effect and its implications, we used a virtual reality (VR) system as an experimental test bed, with haptic sensations delivered via a handheld controller in each hand. We elicited a phantom touch illusion using a technique known as funneling. Funneling provides the user with synchronous vibrotactile stimuli of different amplitudes from controllers that are physically (or, in our case, virtually) linked (Fig. 1C). When human participants hold a controller in each hand with vibrotactile haptics rendered in this manner (Fig. 1D), they experience the haptic sensation as localized in space (“spatialized”). And paradoxically, it “feels like” it originates in the empty space between the two hands (4). What is happening is that, upon the arrival of two near-synchronous tactile cues, the human brain integrates the stimuli. That is, the brain assumes that the two stimuli have a common source—and not just in time, but also in space (5).

Note that this experimental setup serves as an ecologically valid proxy, carefully designed to sensitively probe the potential influence of haptic stimuli, for a variety of teleoperation and immersion tasks. This is important because augmenting such tasks with higher-fidelity haptic sensations may come with the (oft-unstated) assumption that such “improvements” will always yield more realistic and immersive virtual environments. Of course, realism and immersion are subjective perceptions (6), but we can formally assess and quantify them using scientifically established presence questionnaires (7).

We ran several experiments (see the Supplementary Materials) to better understand the dynamics of haptic perception and how to elicit the aforementioned uncanny valley of haptics—and perhaps more importantly, how to avoid it. These experiments studied passive haptic stimulation (i.e., when the participant passively receives a haptic stimulation without moving their arms) contrasted with dynamic haptic stimulation (triggered by the movements of the participant). Research on humanoid robotics has shown that the feelings of unease (or even revulsion) associated with the classic notion of an uncanny valley can be shifted or eliminated (1) by manipulating various aspects of the simulations. For example, cartoonish features can reduce the mismatch between the human-likeness of a robot and its perceived realism (8). To see if a participant’s top-down expectations influenced the results, we also probed causal haptic stimulation with a condition in which users could plausibly attribute an external cause. This took the form of an animated cloud that partially obscured the view of the funneling effect’s location, thereby “explaining away” any discrepancy in haptic sensations.

Our results show that participants could localize the vibrotactile stimuli in different locations (4), establishing the spatial haptic effects. However, the experience—the overall sense of immersion—dipped as this increasing realism of the haptics exceeded the complementary cues (from other senses) in the simulation (Fig. 1B). These findings therefore support the existence of an uncanny valley of haptics.

Likewise, our results demonstrate techniques to reduce and recover from the uncanny valley of haptics. For example, in the dynamic haptic stimulation, asking the participants to perform a motor action was sufficient to provide a “reason” for the haptic sensation, bringing the subjective experience back into agreement with the perceived realism. In addition, in our probe of causal haptic stimulation, providing an animated feature (a moving cloud) that could plausibly “cause” the mismatch between senses was sufficient to preserve the subjective experience.

An uncanny valley of haptics means that designers of human-robot interactions cannot simply assume that more (or more realistic) haptics is better. As experiences move beyond purely visual displays and integrate richer feedback from multiple senses, including haptic and auditory sensations, mismatches become possible and may undermine “improvements” to haptic rendering.

Subjective incongruences produce conflicting percepts across multiple sensory channels. When the human brain subconsciously integrates these conflicting cues into a unified percept (3, 9), the result may be reduced subjective experience (i.e., a decreased sense of immersion). Our finding of an uncanny valley effect for haptics calls for a shift in focus in the design of human-robotic interactions.
from precision to context and suggests a need for a multi-modal approach to haptic feedback—a holistic approach that incorporates multiple human sensory channels into design, rendering, and evaluation of haptic sensations in the user experience.

Although demonstrated in a VR test bed, the effects are rooted in human perception and as such could affect the perceived realism and immersion manifest in many real-world applications, such as teleoperation scenarios, remote robotic manipulation, or even telesurgical tasks. Our study offers insights, methods, and results that may boost future endeavors to render haptic effects that improve (rather than detract from) the overall user experience.

**SUPPLEMENTARY MATERIALS**

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Fig. S1. Reported spatial haptic perception.

Table S1. Questionnaire and factor loadings.

Table S2. Main experiment (passive) results.

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

Movie S1. The uncanny valley of haptics.

Data file S1. Anonymized questionnaire responses for all experiments and conditions.

References (10–15)

**REFERENCES AND NOTES**


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Supplementary Materials for

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

*Corresponding author. Email: margon@microsoft.com

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Table S2. Main experiment (passive) results.
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References (10–15)

Other Supplementary Material for this manuscript includes the following:
(available at robotics.sciencemag.org/cgi/content/full/3/17/eaar7010/DC1)

Movie S1 (.mp4 format). The uncanny valley of haptics.
Data file S1 (Microsoft Excel format). Anonymized questionnaire responses for all experiments and conditions.
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 established 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 = 0.83 (15), and all the KMO values for individual items were above the acceptable limit of 0.5. Bartlett's test of sphericity, $\chi^2 (66)=216$, 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.

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

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.

<table>
<thead>
<tr>
<th>Condition / Condition</th>
<th>Generic Haptics</th>
<th>Spatialized</th>
<th>Visual+Spatialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Haptics</td>
<td>p=0.5, Z=-0.67</td>
<td>p=0.004, Z=2.81</td>
<td>p=0.017, Z=-2.35</td>
</tr>
<tr>
<td>Generic Haptics</td>
<td></td>
<td>p=0.04, Z=-2</td>
<td>p=0.027, Z=2.2</td>
</tr>
<tr>
<td>Spatialized</td>
<td></td>
<td></td>
<td>p=0.0002, Z=-3.65</td>
</tr>
</tbody>
</table>

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 funnelling, 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. |