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Brief article

Empirical evaluation of the uncanny valley hypothesis fails to confirm the predicted effect of motion

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ABSTRACT

The uncanny valley hypothesis states that the acceptability of an artificial character will not increase linearly in relation to its likeness to human form. Instead, after an initial rise in acceptability there will be a pronounced decrease when the character is similar, but not identical to human form (Mori, 1970/2012). Moreover, it has been claimed but never directly tested that movement would accentuate this dip and make moving characters less acceptable. We used a number of full-body animated computer characters along with a parametrically defined motion set to examine the effect of motion quality on the uncanny valley. We found that improving the motion quality systematically improved the acceptability of the characters. In particular, the character classified in the deepest location of the uncanny valley became more acceptable when it was animated. Our results showed that although an uncanny valley was found for static characters, the deepening of the valley with motion, originally predicted by Mori (1970/2012), was not obtained.

1. Introduction

With recent developments in robotics, character animation and virtual environments, the desire has increased for artificial characters to look and behave more like humans. Nevertheless, anecdotal reports indicate that realistic animated characters, like those in the movie *The Polar Express* (Zemeckis, 2004) have received negative reactions from viewers, who complain that the appearance and motion of those characters is uncomfortably realistic (Geller, 2008). Going beyond the scope of movies, observers of some realistic androids, such as those created by Ishiguro (2007), have reported finding them creepy. Indeed, Mori (1970/2012) hypothesised that following an initial rise in acceptability as characters approach a human-like appearance, their acceptability will then suddenly drop when the resemblance becomes too close, and this effect will be accentuated by motion (Fig. 1). The idea of 'acceptability' in this context refers to how acceptable one finds it to interact with a character on a regular basis. The term *uncanny valley* was coined to describe this effect of low acceptability for artificial characters that closely resemble humans, and it is already an established principle for animators and android designers that to avoid the uncanny valley one should focus efforts on the first summit of the curve shown in Fig. 1 (Fabri, Moore, & Hobbs, 2004; Fong, 2003; Mori, 1970/2012). Only recently, however, has psychological evaluation of this hypothesised curve begun to attract empirical scrutiny.

There are several convergent motivations for wanting to more precisely understand the uncanny valley. First, there is the practical benefit that a better understanding could lead to the development of more effective artificial characters. This advancement could arise from a better understanding of how to avoid falling into the valley as well as

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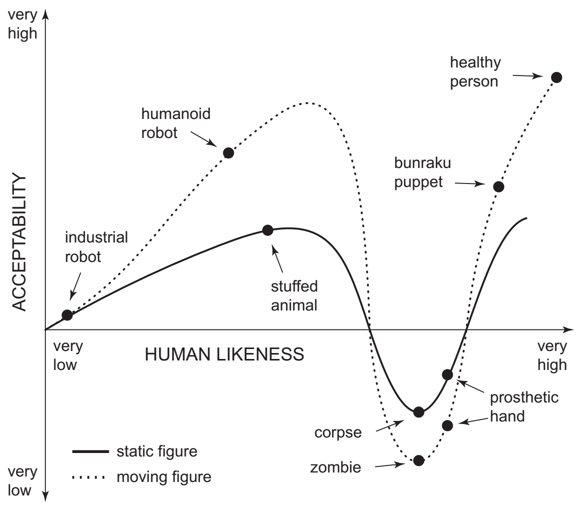

Fig. 1. Adapted from Mori (1970/2012). Hypothesised response of human subjects is plotted against human likeness of the characters. The uncanny valley is the region of negative response to characters that seem highly human like (i.e., zombie and corpse). Movement is hypothesised to change the response for all characters and in particular to deepen the uncanny valley (MacDorman and Ishiguro, 2006; Mori, 1970/2012).

from identifying the fundamental boundaries past which falling into the valley would be inevitable. Second, artificial characters are being used increasingly in perceptual and social interaction studies (Bailenson & Yee, 2005; Boker et al., 2011; Von der Pütten, Krämer, Gratch, & Kang, 2010; Zanbaka, Ulinski, Goolkasian, & Hodges, 2007). Although these artificial characters provide unsurpassed control over stimulus properties, the results obtained with highly realistic characters are often qualified by the possibility that the stimuli might have fallen into the uncanny valley. Finally, at a level fundamental to understanding the psychological phenomenon, there is the theoretical question of why increasing the realism of a configuration of features to levels near those found in natural stimuli produces unappealing results.

Several perceptual, cognitive, and social explanations of the uncanny valley have been advanced, involving a variety of factors including empathy, mate selection, threat avoidance, cognitive dissonance, psychological defences, expectation violation, mismatch of perceptual cues and category boundary effects (Gray & Wegner, 2012; Hanson, 2006; MacDorman, Green, Ho, & Koch, 2009; MacDorman & Ishiguro, 2006; Moore, 2012; Pollick, 2010; Saygin, Chaminade, Ishiguro, Driver, & Frith 2012; Tinwell, 2014). Experiments studying human reactions to original and altered static faces have supported the existence of an uncanny valley effect (MacDorman et al., 2009; Seyama & Nagayama, 2007), as have studies looking at the combination of faces and voices (Kuratate et al., 2009; Mitchell et al., 2011; Tinwell, Grimshaw, Nabi, & Williams, 2011). For example, Tinwell et al. (2011) showed that for speaking virtual characters, a lack of facial expression in the upper parts of the face during speech was found to exaggerate an uncanny valley effect. The explanation for this result was that the absence of upper facial animation accompanying speech elicits a sense of the virtual character resembling a waxwork figure, which makes it difficult to distinguish whether it is real or unreal, and alive or dead, thus producing the sense of uncanniness in the observer (Jentsch, 1906). An uncanny valley effect has also been found in studies using other primates; Steckenfinger and Ghazanfar (2009) examined the viewing preferences of macaque monkeys to static and animated monkey faces. Measuring the duration of eye fixation on the displays, the authors indicated that the monkeys preferred to look at both unrealistic synthetic faces and real faces for a longer period than realistic synthetic faces. Based on their results they concluded that monkeys also experience the uncanny valley phenomenon, making a strong case for the evolutionary origins of this effect (MacDorman et al., 2009). The authors' explanations for the uncanny valley effect in monkeys included such factors as perceived facial attractiveness and high sensitivity to facial abnormalities for realistic synthetic faces.

A number of studies have examined the uncanny valley effect using full body animations and different forms of characters. Chaminade, Hodgins, and Kawato (2007) used a set of animated characters (point-lights, ellipses, robot, alien, clown, jogger) and asked participants to categorise each character's motion as being biological or artificial. The authors reported that the particular form/type of character did not influence sensitivity (d') to motion. Nevertheless, participants judged the characters with the most simple form (point-lights) as moving more naturally than complex characters, which they judged as moving synthetically - a result that is consistent with the uncanny valley prediction (Chaminade et al., 2007). Saygin et al. (2012) used fMRI to assess brain activation by presenting participants with video clips of a human, an android modelled on this human and the same android with its "skin" removed to appear as a mechanical robot. They investigated whether the uncanny valley might be caused by a violation of the brain's prediction that a character that looks a certain way will be associated with particular movements. Indeed, the participants showed similar levels of brain activation when they watched the human and the robot, but increased activation when they watched the android. The authors argued that the android, which appeared human but did not move in a biological manner, violated perceptual expectations, and that this explained the increased brain activation.

Although the findings of Chaminade et al. (2007) and Saygin et al. (2012) support the idea that motion influences the uncanny valley, other studies have provided mixed results. Steckenfinger and Ghazanfar's (2009) study with macaque monkeys showed that the uncanny valley effect was more apparent for animated than static faces. However, the authors argued that facial motion was not a prominent cause of the uncanny valley, highlighting the influence of static facial features in eliciting an uncanny valley response. In another study, Thompson, Trafton, and McKnight (2011) parametrically manipulated three kinematic features of two different computer generated characters (human and mannequin) and examined the effects of those manipulations on judgments of humanness, familiarity, and eeriness. Participants rated those characters with more natural movement as being more human-like, more familiar, and less eerie. Thompson et al. (2011) concluded that this pattern of results was inconsistent with the influence of motion predicted by the uncanny valley hypothesis.

Our main motivation was to clarify the ambiguous situation regarding the role of motion and how it might interact with form in producing the uncanny valley effect. We created a full range of different characters and used both still images and animations in a manner directly motivated by the original thought experiment of Mori (1970/2012), to better understand the impact of characters' forms in static and dynamic conditions. The animations were based on motion capture data of actual human movement and parametrically degraded versions of the same movement. Our results indicate that the uncanny valley was found for the static characters, but that the deepening of the valley with movement predicted by Mori did not occur, instead movement diminished the impact of the uncanny valley.

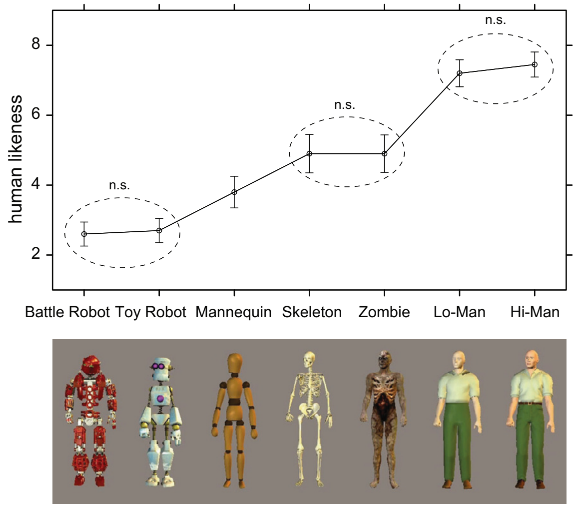

Fig. 2. Mean human likeness ratings plotted with standard error bars for each character. Underneath the mean human likeness ratings are the static images of each character. Pairwise comparisons revealed that only three pairs of characters are not significantly different in the human likeness ratings they received. Those three pairs of characters are marked with dashed circles.

2. Materials and procedure

2.1. Stimuli

The original thought experiment of Mori (1970/2012), illustrated in Fig. 1, included characters such as a toy, a corpse and a live person, and considered the acceptability of these characters to be a function of human likeness for both static and moving characters. Our goal was to examine this predicted relationship empirically. Acceptability was operationalised in terms of how acceptable one finds it to interact with a character on a regular basis. The ratings of acceptability formed the y-axis of the plots of the uncanny valley. One might debate whether acceptability is the best translation of the Japanese term *shinwakan* used by Mori to define the y-axis (Mori, 1970/2012); it turns out, in fact, that *shinwakan* is a neologism in Japanese and the other translations refer to it as rapport, familiarity and also likeability (Bartneck, Kanda, Ishiguro, & Hagita, 2007; Ho & MacDorman, 2010). Our use of the term acceptability, which we explained as being how comfortable a person would feel being in regular contact with the character, was designed to capture the essence of these different translations.

To create the stimuli we started by choosing seven 3D computer characters that included ones similar to those suggested by Mori: battle robot, toy robot, mannequin, skeleton, zombie, and low- and high-quality man (see bottom of Fig. 2 for images of characters used). All the characters were presented in the frontal orientation, facing the observer. To animate these characters, we used motion capture data of an individual knocking on a door with their right hand in a neutral manner (Ma, Paterson, & Pollick, 2006). This motion capture data represented each posture of the motion sequence as a hierarchical set of joint angles using a forward kinematics model.

In addition to this natural motion capture data, we created a set of increasingly distorted versions of the same knocking movements using MATLAB software (MathWorks) Natural human movement is generally smooth and accomplished by moving multiple joints simultaneously to create an end-effector (e.g., wrist) trajectory with a bell-shaped speed profile (Flash & Hogan, 1985; Rosenbaum, 2009). The distortions we introduced had the goal of making the motion less natural by disrupting simultaneous movement of the joints of the arm. This was achieved by locking the shoulder joint angle constant whilst allowing the elbow to move, and then switching to locking the elbow joint angle constant whilst letting the shoulder joint move, and continuing this alternation for the duration of the movement (Fig. 3). While our distortions were not meant to mimic any particular human condition (except perhaps a dancer performing a robot dance), locking joints while performing a task simplifies motor planning and is reminiscent of the way we perform complex actions when we first learn them (Bernstein, 1967) as well as how simple robot controllers move to a goal posture by sequentially moving individual joints. To implement a means by which we could lock individual joints we manipulated the hierarchical joint-angle representation of the body provided by our motion capture data. Manipulation of joint-angle representations are common in studying the perception of animated (Hodgins, O'Brien, & Tumblin, 1998) and robot (Pollick, Hale, & Tzoneva-Hadjigeorgieva, 2005) characters but have only recently gained more use in biological motion perception (Thompson et al., 2011). For example, Thompson et al. (2011) used techniques similar to ours to degrade natural walking movements, including parametrically changing the extent of joint angle excursions. For our stimuli we obtained parametric control of the level of distortion by varying the duration for which joints were locked. The starting time of the alternating locking of joints was random, to avoid forming a regular covariation with the movement itself, and linear interpolation was used at the beginning and end of each joint locking to prevent the movement from appearing excessively jerky. Given the

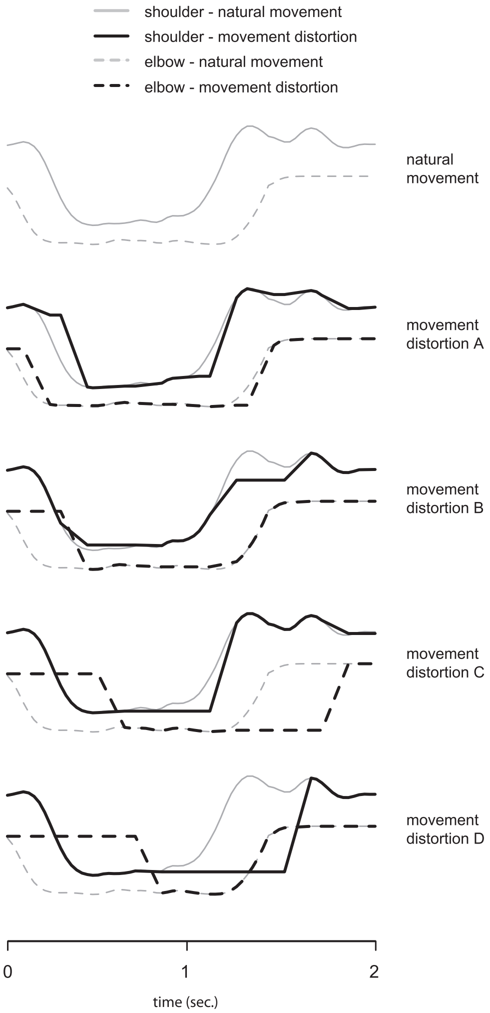

Fig. 3. Five plots illustrating the results of the movement distortion procedure. Each graph shows only a single component of the shoulder and elbow joint angles. The top plot shows the original natural joint angles in light grey, and this trace is shown for comparison in the following graphs. The distortion alternated locking the shoulder and elbow joints, and for increasing distortion this lock period increased in duration (from A to D). The period of a joint being locked is evident from the joint angle trace appearing as a horizontal line.

alternation of joint angles being locked, the trajectory of the wrist followed approximately the same trajectory even for the highest distortion and thus the movement was still recognisable as the same action and had approximately the same average speed. However, for natural actions the speed profile of the wrist had two distinct and smooth peaks corresponding to the raising and lowering of the hand, and this clear pattern broke down for large distortions. To increase the variety of the motion in our study, we used six different neutral knocking actions from the same library (Ma et al., 2006). Once the set of distorted motions was created, two-second *quicktime* movies of the static and animated characters were generated using Poser 6 software (Curious Labs, 2005; see Supplementary Movie for an example of movies).

2.2. Participants

Forty participants (mean age = 25, SD = 4.7) were recruited from the University of Glasgow, Department of Psychology participant pool and were paid for their participation. Participants were assigned to one of two experimental groups: human likeness ratings and acceptability ratings, and they were naive to the purpose of the experiment. All participants gave written informed consent, and all procedures were approved by the Ethical Committee at the School of Psychology, University of Glasgow.

2.3. Procedure

Stimuli were presented on a 19-in. CRT monitor with a resolution of 1280×1024 pixels. The animated characters had a height of approximately 6.1 degrees and a width of approximately 4.3° of visual arc at a viewing distance of 75 cm. For both experimental groups (human likeness ratings and acceptability ratings) the order of stimuli was randomised. In the human likeness ratings group, participants were shown a static image of a character for two seconds. After each image, participants gave ratings of human likeness on a 9-point Likert scale (1 – very non-humanlike, 9 – very humanlike). In the acceptability ratings group, participants were shown two-second-long videos of the complete set of animated characters performing a knocking action at every level of movement distortion. The acceptability ratings group were also shown a static image of each of the characters. These were presented either at the start or end of the movie testing phase, with the presentation order being counterbalanced across participants. Because we were concerned that the motion implied within a static frame might influence acceptability of the static frames, we ran a control experiment to confirm that there was no effect of the choice of static frame on acceptability.[2] For both the static and moving character, after each presentation the participants were required to rate the character's acceptability on a 9-point Likert scale (1 – totally unacceptable, 9 – totally acceptable) by pressing the appropriate number (1–9) on the keyboard. Participants were encouraged to go with their first impressions for their answer. The displays were presented and responses collected with the Psychophysics Toolbox for MATLAB (Brainard, 1997; Pelli, 1997). Each participant in the acceptability ratings group viewed three repetitions of six variations of the knocking action, at a natural plus four distorted levels of the movement, for each of seven characters, presented across five blocks (total of 630 movie displays and seven static displays).

[2] We also conducted a control experiment to examine whether there was any effect of different knocking postures in the static images. Five frames from the knocking action were selected, from hand down at the side of the body to up by the head at the peak of the movement. We presented 28 participants with those five knocking postures as static images for each character and obtained acceptability ratings. We found no significant effect of posture ($F(4,104) = 3.2$, $p = 0.06$) and no interaction between character and posture ($F(24,624) = 1.76$, $p = 0.08$), indicating that the knocking posture in the static images had no effect on how acceptable characters were judged.

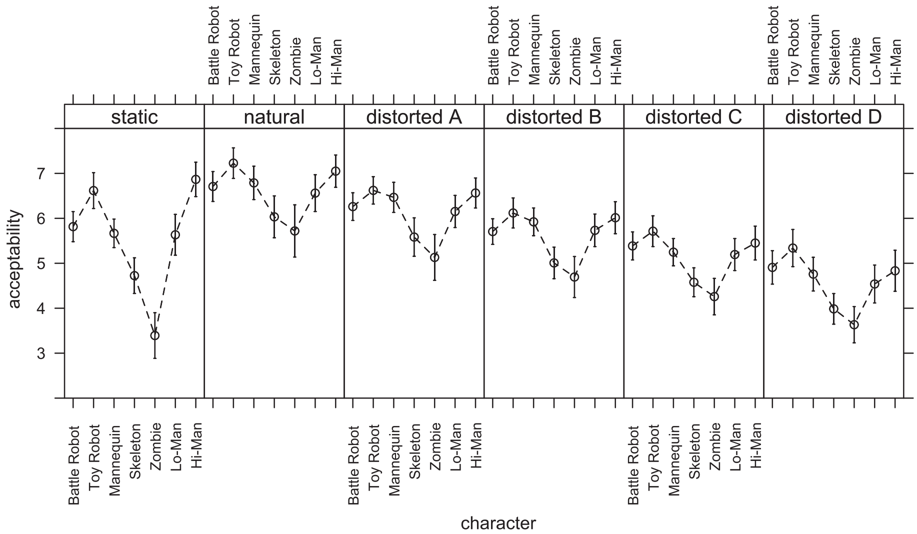

Fig. 4. Mean acceptability ratings with standard error are plotted for each character. Separate panels represent different levels of movement: natural movement and four levels of movement distortion (from A to D) as well as the static images (leftmost panel).

3. Results

We examined the human likeness and acceptability ratings separately. Greenhouse–Geisser correction was used for all tests due to violation of the sphericity assumption. The one-way ANOVA carried out on the human likeness ratings showed a main effect of character ($F(3.723, 70.737) = 33.277$, $p < 0.001$, partial $\eta^2 = 0.637$), indicating that there were significant differences in human likeness ratings for different characters (Fig. 2). For the acceptability ratings we first confirmed that there was not an effect of whether the acceptability ratings of static characters came before or after the judgments of moving characters ($F(1,18) = 0.31$, $p = 0.59$). We then collapsed across this order variable to examine participants' acceptability ratings using the factors of character and motion in an ANOVA. Results showed significant main effects of character ($F(2.874,54.601) = 6.033$, $p = 0.001$, partial $\eta^2 = 0.241$) and motion ($F(1.613,30.640) = 15.311$, $p < 0.001$, partial $\eta^2 = 0.446$), and a significant interaction between these ($F(4.683,88.985) = 3.928$, $p = 0.004$, partial $\eta^2 = 0.171$). A post hoc analysis comparing means for all characters and levels of motion was performed, revealing that although degrading motion had a generally negative effect on all characters, the change in acceptability from static to naturally moving differed depending upon the character (see Supplementary Fig. 1). Of particular relevance to the original claim that motion deepens the uncanny valley, Tukey posthoc analysis showed that the naturally moving zombie was significantly more acceptable than the static zombie ($q = -6.38$, $p < 0.01$).

Averaged acceptability ratings with standard error bars were plotted for each character within each level of motion (Fig. 4). In order to visualise the acceptability results in the framework originally proposed by Mori (1970/2012) (Fig. 1) we rank ordered the different characters using the human likeness ratings shown earlier in Fig. 2. These results revealed the hypothesised uncanny valley in several aspects. Importantly, the static figure is entirely consistent with the relation hypothesised by Mori. However, contrasting the static condition with the natural motion reveals that there was no deepening of the uncanny valley for the naturally moving zombie character; instead there was much greater acceptability, which goes against the prediction illustrated in Fig. 1. In effect, motion raised the undead from the uncanny valley by increasing the acceptability of the zombie.[3] The effect of motion is also visible in Fig. 4 where we can see that increasing movement distortion leads to a lowering of acceptability of all characters from their values with natural motion.

4. Discussion

In the present study we examined the role of form and motion in the context of the uncanny valley. We designed our experiment around the original thought experiment of Mori (1970/2012) by using similar types of static characters to those discussed by Mori. To explore the claim that motion deepens the uncanny valley, we generated animations of natural movements and a set of animations in which the movements were parametrically degraded for these characters. The results for static characters conformed to the prediction of Mori that dead characters (i.e., zombie and skeleton) were at the deepest locations of the uncanny valley. However, our results with the moving characters disagreed with the prediction of Mori, in

[3] To better understand whether motion led to a simple compression of the range of responses or to a genuine raising of the valley, we normalised the data to have mean zero and overlaid the plots for each movement distortion. The results, shown in Supplementary Fig. 2, indicate that indeed, the moving zombie is "raised" from the uncanny valley relative to acceptability ratings for the static zombie. For characters outside the uncanny valley acceptability ratings are comparable between static and moving conditions.

that the zombie character at the bottom of the uncanny valley was raised in acceptability when animated. Future research is needed to reconcile this finding with the potential role of motion in the uncanny valley.

Our finding that an uncanny valley effect was obtained for static figures of the human body is consistent with the existing empirical literature on faces and thus provides empirical evidence for a similar role of the uncanny valley in body perception. The results using static faces have demonstrated how facial features such as skin texture (MacDorman et al., 2009), distance between facial features (MacDorman et al., 2009; Seyama & Nagayama, 2007) and size of the eyes (Seyama & Nagayama, 2007) can be used to obtain an uncanny valley effect. Results from experiments investigating body motion are less direct, but support the idea that motion improves the acceptability of computer characters. Thompson et al. (2011) displayed walkers in the form of mannequins or full body actors (similar to our high resolution man) and showed that degrading the motion of these characters led to lowered familiarity ratings, which is consistent with our lowered acceptability ratings with motion degradation. Similarly, McDonnell, Breidt, and Bülthoff (2012) compared the perceptions of static images depicting faces to moving images of faces on a range of human-like characters from cartoon form to photorealistic and found that motion improved the familiarity ratings across this range of characters. This finding by McDonnell, Breidt, and Bülthoff (2012) is useful, because the range of characters used for their study began approximately with our low-resolution man and extend past our high-resolution man into the realm of photorealism. Thus, provided that results from facial motion generalise to body motion we have evidence that the general advantage for moving displays found in our experiment continues with increasing human likeness.

The fact that the zombie character was raised in acceptability has implications for various theories of the uncanny valley. One view of the uncanny valley can be roughly stated as the uncanny stimulus engendering some kind of fear. This could be fear of death (MacDorman & Ishiguro, 2006), fear of a mind in a machine (Gray & Wegner, 2012), or fear of attachment (Tinwell, 2014). We can also speculate that the fear might arise simply from the association with modern media and culture that frequently use images of zombies to produce a fearful response in viewers. Regardless of the cause, our results suggest that natural motion reduces the fear produced by these static images. Another view of the uncanny valley proposed by Saygin et al. (2012) is reminiscent of explanations based on expectation violation (MacDorman & Ishiguro, 2006) and holds that the uncanny valley arises out of prediction error due to the mismatch of form and motion. In this fMRI study they found stronger responses for a physical android character that appeared human but did not move biologically, than for either a human moving biologically or a robot moving robotically. This brain imaging result could explain our finding that the hi-man character was less acceptable when moving with a large distortion. However, it is a topic open for future research as to how coding of prediction error might explain why the zombie character improved in acceptability with more natural motion. One factor relevant to this discussion of how the form and motion of characters would combine is what is known in the multisensory research community as the *unity effect*, which predicts that whether or not a participant assumes that different cues "go together" influences how they combine (Vatakis & Spence, 2007; Welch & Warren, 1980). A possible way forward to systematically explore this issue would be in the context of the recently proposed Bayesian categorisation model of the uncanny valley (Moore, 2012). This model recognises that the mapping of multiple perceptual cues into categories can give rise to tension at the categorical boundary and provides an explanation of how this can lead to complex patterns of response.

In conclusion, although the concept of the uncanny valley has been around for over 40 years, an important claim about it – that motion deepens the valley – has never been empirically tested. We performed this test and our results showed that while an uncanny valley held for static images, when natural motion was introduced the depth of the uncanny valley became shallower. Thus, a basic and commonly stated premise of the original uncanny valley thought experiment does not withstand empirical test. This is an important result in advancing our understanding of the uncanny valley and guiding future research into how to design artificial characters with greater acceptability.

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L.P. and L.M. contributed equally to this work. We would like to thank Gavin White for his assistance at the start of this project and to the reviewers for their useful suggestions. We also gratefully acknowledge the ESRC for their support of L.P.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2013.11.001.

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