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A Literature Review of the Research on the Uncanny Valley

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Abstract. Depend on the development of science and technology, the demands for robots are not only limited to the use of functions but also pay more attention to the emotional experience brought by the products. However, as the robot's appearance approach human-likeness, it makes people uncomfortable, which is called the Uncanny Valley (UV). In this paper, we systematically review the hypothesis and internal mechanisms of UV. Then we focus on the methodological limitations of previous studies, including terms, assessment, and materials. At last, we summarize the applications in interaction design to avoid the uncanny valley and propose future directions.

Keywords: Uncanny Valley, Humanoid Robots, Human-Computer Interaction, Affective Design, Human-likeness

1 Introduction

With the boom of computer technology and the development of related hardware facilities, robots have been used more and more widely in human society and provided many conveniences to people's life [1]. In the past 20 years, social robots have developed fast and been used to interact with humans in many places, such as homes, hospitals, and shopping malls [1]. In order to improve human-robot interaction, engineers have designed robots that resemble humans highly [2]. There is a positive relationship between the human-likeness of robots and feelings of comfort with them. However, it has a steep dip in comfort and felt eeriness when robots looked almost but not entirely human, which called the "uncanny valley" [3].

The concept of "uncanny valley" was first proposed by Mori in 1970 [4]. In his paper, he envisioned people's reactions to robots that looked and acted almost like a human and took some examples to verify his thought. He proposed that the level of affinity for the robot increased up with its appearance becoming more humanlike until people perceived the faces as eerie suddenly. However, as the robot's human-likeness went on increasing, the eeriness reverted to likeability. This concept is useful to design a robot and works as a guide to improve human-robot interaction.

This paper systematically combs the explanation and internal mechanisms of the uncanny valley, the problems and deficiencies in existing research, and its practical applications in interaction design. The paper has the following structure. In Section 2, we describe different explanations of the uncanny valley. In Section 3, we present the defects of existing research, including the terms, assessments, and materials. In Section 4, we summarize the application of the phenomenon in the design of robots to avoid the uncanny valley.

2 Explanations of the Uncanny Valley

Researchers have proposed a variety of explanations to account for the uncanny valley phenomenon [2]. These hypotheses can be mainly divided into two categories. One category explains the phenomenon from an evolutionary psychology perspective that the uncanny feeling comes from facial features themselves, including the Threat Avoidance hypothesis [2, 3, 5, 6] and the Evolutionary Aesthetics hypothesis [2, 5, 6]. The other category interprets the phenomenon based on cognitive conflicts, including the Mind Perception hypothesis [1, 7], the Violation of Expectation hypothesis [1-3, 5], and the Categorical Uncertainty hypothesis [1, 2, 8]. Most related empirical studies focus on the latter because the cognitive response is easy to quantify and manipulate. However, the hypothesis of evolutionary psychology has little empirical research.

2.1 Explanations based on evolutionary psychology

Threat Avoidance hypothesis. Mori [3] first pointed out that the UV phenomenon "may be important to our self-preservation". During the process of evolution, diseases and death are two main threats to human beings. Thus, there are two explanations for the uncanny valley stemming from the avoidance of threat. The first explanation is called pathogen avoidance, which indicates that when people perceive the imperfections of humanoid robots, they will associate the defects with diseases [2]. Moreover, because of the high human-likeness, people may consider that humanoid robots are genetically close to humans and are likely to transmit diseases to humans [2, 5, 6]. However, this hypothesis is just an inference based on Rozin's theory of disgust and has not been tested directly [2, 5]. Another explanation named mortality salience was proposed based on the terror management theory. Hanson [9] indicated that the flaws of humanoid robots combined with a humanlike appearance could remind us of mortality. From the aspect of this explanation, the uncanny feeling is the anxiety for mortality and the fear of death triggered by humanoid robots. People may be reminded of death and consider humanoid robots as dead individuals who come alive [2, 5]. However, there is only one study testing the hypothesis directly and found that the sensitivity to the vulnerability and impermanence of the physical body was significantly correlated with eerie ratings of android [10].

Evolutionary Aesthetics hypothesis. The hypothesis pays attention to the attractiveness of physical features and regards the uncanny feeling as an aversion to unattractive individuals. By morphing the images of abstract robots and realistic robots or real humans, Hanson's research [9] found that the high-attractive images were consistently rated low in eeriness. Attractiveness is judged based on specific external characteristics that humans are sensitive to, such as bilateral symmetry, facial proportions, and skin quality [6]. These traits are associated with health, fertility, and other aspects that are close to the reproduction, and we inherit the preference for these traits from our ancestors who successfully reproduced under the selection pressure [2, 5, 6]. In a word, aesthetic properties are shaped by natural selection and determine the feeling of humanoid robots potentially.

These hypotheses explain the uncanny valley from the perspective of evolutionary psychology. Although they focus on various mechanisms to suggest the explanations, the essence is to achieve self-preservation and successful reproduction, which is the core of evolutionary psychology. However, the empirical studies supporting these hypotheses are still insufficient [2].

2.2 Explanations based on cognitive conflicts

Mind Perception hypothesis. Gray & Wegner [7] proposed that humanoid robots are uncanny because they are so realistic that people may ascribe to them the capacity to feel and sense. However, this capacity is considered as the unique characteristic of humans, which is not expected to emerge on the robots [2, 7]. People are happy to have robots do works as human, but not have feelings like humans.

Violation of Expectation hypothesis. This hypothesis expands the mind perception hypothesis and believes that people will elicit specific expectations of the humanoid robots whose appearance resembles that of humans. For example, humanoid robots are expected to perform movements or speak as smoothly as humans. However, the robots often violate these expectations: the movements may perform mechanically, and the voice may be synthetic [2, 5]. The mismatch between expectations and reality results in negative emotional appraisal and avoidance behaviors, and leads to the feelings of eeriness and coldness [1, 11].

Categorical Uncertainty hypothesis. The hypothesis emphasizes that the feeling of eeriness is caused by the ambiguous boundary of categories [2, 5, 6]. There are many empirical studies on this hypothesis, but the results are quite controversial. Some studies support the Mori's uncanny valley that the most humanlike robots are perceived as the robots. This perception blurs the category boundary between humans and machines to the greatest extent [12]. However, Ferrey, Burleigh, & Fenske's study [13] employed human-robot and human-animal morphing images, and found that the negative peak is not always close to the human end (Line 1 in **Fig. 1**). The perceptual ambiguity was maximum at the midpoint of each continuum (Boundary 1 in **Fig. 1**). Furthermore, recent research found that the location of the category boundary did not coincide with the classic uncanny valley either (Boundary 2 in **Fig. 1**), and the negative peak was near the machine end (Line 2 in **Fig. 1**) [14].

These hypotheses interpret the uncanny valley based on cognitive conflicts. The conflict may exist between deduction and stereotype, between expectation and reality, or between different categories. Although there are many related empirical studies because the cognitive response is easy to quantify and manipulate, the explanation of the uncanny valley is still controversial.

3 Defects of Existing Research

At present, the related research of the uncanny valley involves computer science, psychology, material science, and other fields. Researchers studied the feelings of eeriness from various groups of users [15, 16], and explore the methods to improve the design of androids or computer-animated characters [14, 17, 18]. However, there are some problems in the existing studies, which may lead to inconsistent findings.

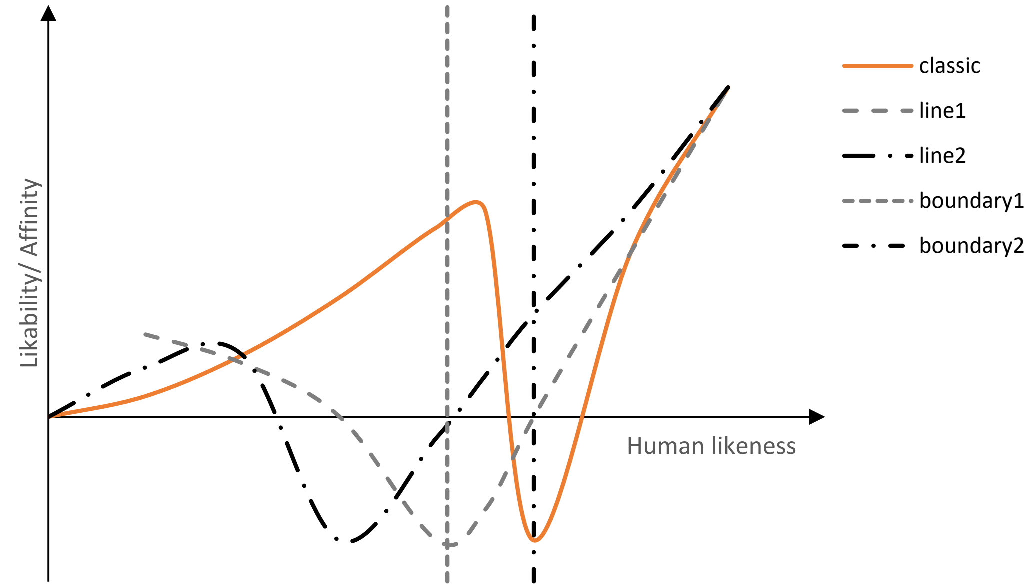

Fig. 1. The uncanny valley in different studies

The classic uncanny valley is proposed by Mori. Line 1 is proposed by Ferrey, Burleigh, & Fenske (2015). Line 2 is proposed by Mathur, Reichling, & Lunardini, et al. (2020). Boundary 1 and 2 exhibit the category boundary in Ferrari et al. and Mathur et al.'s study, respectively.

3.1 Terms

Firstly, the absence of a clear definition of uncanny feelings may be a major cause of the controversial findings [19-21], especially the inconsistency of the translation [1]. Mori [4] used "shinwakan" or "bukimi" to represent the feelings when people faced different human replicas (e.g., androids or artifacts), when the feelings changed against human-likeness [22]. The original Japanese term "bukimi" was translated clearly into eeriness. However, the word "shinwakan" was first translated into familiarity, which was not equivalent and proved complex to define, partly because of its two meanings in English-a sense of closeness or lack of novelty [22-25]. Thus, it is no surprise that Mori's original items have been extended to various interpretations and used in numerous studies. Realizing that, Mori et al. [3] revised the translation of familiarity into affinity, which refers to novelty or strangeness. Unfortunately, according to the literature review recently, although affinity has been used in some research, it is still not accepted and used consistently (**Table 1**).

Moreover, the same term can be explained as different connotations in various studies. For instance, "likability" is interpreted as friendly and enjoyable [14, 26], or aesthetic or pleasant appearance of the character [21]. Distinct instructions result in complicated comprehension.

One more reason for the dilemma may be that a single concept could not cover the uncanny feeling. Ho et al. [27] verified that uncanny feeling includes several kinds of emotions, such as fear, disgust, nervousness, dislike, and shock. Future research is encouraged to adopt a universal definition of the original term “shinwakan”, such as affinity [28], as well as confirm its boundaries and content compositions.

Table 1. List of items used in different studies

Original Item	Item	Author & Year
Positive Shinwakan	Acceptability	Hanson, Olney, & Prilliman et al., 2005
	Affinity	Mori, MacDorman, & Kageki, 2012; Zibrek, Kokkinara, & McDonnell, 2018; Kätsyri, Gelder, & Takala, 2019, Study 2&3
	Appeal	Hanson, 2005
	Attractiveness	Ho & MacDorman, 2010; Burleigh, Schoenherr, & Lacroix, 2013, Study 1; Destephe, Zecca, & Hashimoto et al., 2014; Ho & MacDorman, 2017
	Familiarity	Hanson, 2005; MacDorman & Ishiguro, 2006; MacDorman, 2006; Bartneck, Kanda, & Ishiguro et al., 2009; Cheetham, Wu, & Pauli et al., 2015, Study 2; Chattopadhyay & MacDorman, 2016; MacDorman & Chattopadhyay, 2017; Schwind, Floerke, & Ju et al., 2018; Pütten, Krämer, & Maderwald et al., 2019
	Pleasantness /Pleasure	Seyama & Nagayama, 2007; Ho & MacDorman, 2010; Burleigh, Schoenherr, &Lacroix, 2013, study 2
	Likability	Bartneck, Kanda, & Ishiguro et al., 2007; Ferrey, Burleigh, & Fenske et al., 2015; Zlotowski, Sumioka, & Nishio et al., 2015; Mathur & Reichling, 2016; Kätsyri, Mäkäränen, & Takala, 2017; Pütten, Krämer, & Maderwald et al., 2019; Mathur, Reichling, & Lunardini et al.,2020
	Valence and Arousal	Cheetham, Suter, & Jäncke, 2011; Cheetham & Jancke, 2013; Cheetham, Wu, & Pauli et al., 2015, Study 1
	Warmth	Ho & MacDorman 2010; MacDorman & Entezari,2015; Chattopadhyay & MacDorman, 2016; MacDorman & Chattopadhyay, 2016; Ho & MacDorman, 2017
Negative Bukimi	Eeriness	Hanson, 2005; MacDorman, 2006; MacDorman & Ishiguro, 2006; Bartneck, Kanda, & Ishiguro et al., 2009; Ho & MacDorman, 2010; Burleigh, Schoenherr, &Lacroix, 2013; Destephe, Zecca, & Hashimoto et al., 2014; Strait & Scheutz, 2014; Zlotowski, Sumioka, & Nishio et al., 2015; Chattopadhyay & MacDorman, 2016; Koschate, Potter, & Bremner et al., 2016; MacDorman & Chattopadhyay, 2016; Kätsyri, Mäkäränen, & Takala, 2017; MacDorman & Chattopadhyay, 2017; Strait, Floerke, &Ju et al., 2017; Buckingham, Parr, & Wood et al.,2019; Kätsyri, Gelder, & Takala, 2019, study 1; Appel, Izydorczyk, & Weber et al.,2020

3.2 Assessments

Self-report questionnaires are widely used in previous studies. Gray & Wegner [7] used the Likert scale to collect the participants’ feelings of uneasy, unnerved, and creepy. Meanwhile, different scales were employed, such as a visual analog scale [14, 26], single-target IAT [29], and semantic differential scale [30, 31]. However, there are several potential limitations. Firstly, the construct validity of these questionnaires and scales are still questioned. For example, some dimensions include only one item, and some dimensions are highly correlated [2, 26, 32, 33]. Secondly, there are few suitable external calibrations to test whether the items measure the putative inner constructs (emotions). The assessment of uncanny feelings is subjective and lacks objective indexes [2]. Thirdly, psychometric noise will also bring an impact on the effectiveness of subjective rating [2]. Subjects may also give socially desirable responses [33].

Recently, objective indicators with high sensitivity, such as reaction times, pupillary responses, EMG (facial electromyography), and brain activity (ERPs and fMRI), are gradually adopted in this area

[34-39]. For example, an fMRI study found that VMPFC (the ventromedial prefrontal cortex) integrates likability and human-likeness to an explicit UV reaction [39]. The fMRI technology used to explore uncanny feelings could go back to 2011 [40], while eye-tracking data collected firstly to study monkeys' uncanny feelings in 2009 [41]. Thus, objective indexes and measurements are expected to determine the occurrence and operation mechanisms of uncanny feelings.

3.3 Materials

The selection criteria of experimental materials are not consistent [10, 26]. Similar to uncanny feelings, human-likeness is also a complex variable without a unified definition [24]. Therefore, various stimuli used in previous research induce irrelevant variables that may lead to confounding results. **Table 2** shows the stimuli used in the experiments which aim to verify the UV effect in the past five years.

Participants were asked to make evaluations based on different forms of stimuli, such as videos, pictures, descriptions, words, or even interactions [14, 17, 21, 24, 29, 42, 43]. However, few studies compared the uncanny feelings evoked by these various mediums directly. Moreover, it is also difficult to infer whether people had similar feelings when they only see a part of the robots (e.g., face, head, or body), even all of them are displayed as static graphs. [14, 26, 39, 44]. Furthermore, a small number of discontinuous stimuli could not reflect the continuous axis of human-likeness correctly. Bartneck et al. [24] got a result against Mori's prediction, but the author pointed out that by using one human and his robotic copy as the stimuli was unable to confirm or disconfirm the Mori's hypothesis. If the stimuli are arbitrarily or subjectively selected, then researchers would not be possible to obtain reliable conclusions of the UV effect [25].

Additionally, morphing artifact becomes one of the common methods to manipulate stimuli [20]. Following the guidelines that endpoint images should be similar to each other to reduce morphing artifacts [45], using similar source images of humans and robots for morphing restrict the generated range of human-likeness [31]. Even if the morphing artifacts controlled perfectly, it is still questioned whether the objectively manipulated human-likeness percentages are equal to perceived human-likeness [31, 45].

4 Practical Applications

The relevant research results of the uncanny valley, which involve users' attitudes and concepts towards humanoid robots, play a significant role in the field of human-computer interaction, especially in interaction design. The development and innovation of humanoid robot design are trying to reduce the negative impact of the uncanny valley. From the perspective of a human, the question is whether the individual differences among the users can predict sensitivity to the uncanny valley and acceptance to the humanoid robots [10, 46]. From the view of the robot, the question is what kind of design is more acceptable to the majority of users [9, 46]. Therefore, in order to avoid the uncanny valley, there are two directions to improve the design of robots.

One way is to pursuit a nonhuman design deliberately so that the robots can lie at the first peak of affinity. Find a moderate degree of human likeness and a considerable sense of affinity, rather than taking the risk to increase the degree of human likeness continually [3]. There are two suggestions:

Table 2. Stimuli used in the past five years

Author & Year	Medium				Display				Serialization		Artificiality			Reponse	Amount of Stimuli
	Video	Gragh	Vignette	Others	Face	Head	Whole body	Others	Independent or Scattered	Series	Nature	Both Nature & Artificial	Artificial		
Mathur, Reichling, & Lunardini, et al., 2020		●			●					●	●			On-line	80 face pictures
Appel, Izydorczyk, & Weber et al., 2020, Study 1			●					●	●				●	On-line	3 short descriptions of robot
Villacampa, Ingram, & Rosa, 2019		●			●				●		●			Laboratory	5 faces
Pütten, Krämer, & Maderwald et al., 2019		●					●		●			●		Laboratory	36 pictures of 6 stimulus categories
Kätsyri, Gelder, & Takala, 2019, Study 1		●			●					●		●		On-line	60 faces pictures of 6 actors
Reuten, Dam, & Naber, 2018		●			●					●			●	Laboratory	8 face pictures
MacDorman & Chattopadhyay, 2017		●			●					●		●		On-line	7 face pictures
Strait, Floerke, & Ju et al., 2017		●						●	●		●			Laboratory	60 half-body pictures
Ho & MacDorman, 2017, Study 4	●							●	●		●			On-line	12 video clips of 12 characters
Kätsyri, Mäkäräinen, & Takala, 2017	●						●		●		●			Laboratory	60 video clips of 15 movies
Wang & Rocha, 2017, Study 1		●			●				●		●			Laboratory	89 face pictures
Mathur & Reichling, 2016, Study 1		●				●			●		●			On-line	80 face pictures

Note: "Medium" means the form of stimuli presentation. "Display" means which part of the stimuli could be observed. "Serialization" means whether the stimuli are series of many components, such as a series of morphing images. "Artificiality" means whether the stimuli were morphed, for example, a photo of robot from Google or filmed is natural.

(1) *Keep the balance between humanness and machine-like.* The existence of the nose, eyelids, and mouth can increase the perception of humanness. Several design suggestions are proposed, for example, four or more features on the head, wide head with wide eyes, details in the eyes, or complex curves in the forehead [47].

(2) *Design the robots for target users*. For example, children rate human-machine like robots as the most positive, and they prefer cartoon-like and mechanical features, such as exaggerated facial features and wheels [48-50]. Elderly users have their preferences as well [46].

The other way is to reach the second peak and increase the level of human-likeness to step over the uncanny valley. The main idea of this way is to narrow the gap between robots and humans from various aspects:

(1) *Make robots alive.* Hanson [9] indicated that people feel unease because robots seem partly-dead. For example, robots shut down instead of going to sleep like humans. Thus, it is better to remove these flaws to make robots alive, friendly, and attractive.

(2) *Express emotions.* The addition of emotion display (e.g., emotional expressions, gait, voice, or gestures) can decrease the sense of uncanniness successfully [18, 51]. These emotion displays narrow the gap between the expectation the design raises about human nature and the perception of it, achieving a harmonious interaction.

5 Conclusions and Future Directions

Robots are becoming increasingly prevalent in everyday life. Humanoid robots are expected to be used more friendly and experienced more comfortably. Therefore, how to define and design the best appearances of humanoid robots is a critical question to be answered. In summary, decades of research develop two main explanations of the uncanny valley effect from the views of evolutionary psychology and cognitive conflict. The inconsistency of previous studies may be due to the absence of a unified definition, robust measure, and the representativeness of materials. Practically, pursuit a nonhuman design and increase the rate of human-likeness as high as possible are both helpful to avoid uncanny feelings. Future research is encouraged to reach a consensus on how to define the uncanny feelings, no matter it is a single item or complex emotions. Moreover, creating a sizeable and diverse database of images (or videos) covers a continuous series of human-likeness, as created by Mathur et al. [14], could avoid manipulation defects such as heterogeneous or discontinuous stimuli. Finally, considering most of the previous studies focus on young adults, future research is expected to test the uncanny valley in a more diverse user group.

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