The Novelty in the Uncanny

Designing Interactions to Change First Impressions

MAIKE PAETZEL-PRÜSMANN
Abstract

In 1970, Japanese researcher Masahiro Mori published a seminal paper where he hypothesized that robots that appear human-like but are still distinguishable from being human would not attract people towards them, but instead cause an uncanny sensation. This phenomenon, known as the uncanny valley effect, has been widely studied within the social robotics community, and a multitude of experiments have since been conducted supporting Mori’s hypothesis. The specifics of a robot’s appearance and behavior leading to such an uncanny sensation, however, remain an open research question and require further study. These gaps in the causal relationship between uncanny feelings and a robot’s design have lead uncanniness being increasingly used to explain any lack of enthusiasm towards robots, both in the scientific community and the general public. It is then often implicitly assumed that uncanny feelings towards a robot have damaging consequences for long-term human-robot interaction. Most empirical studies on the subject, however, focus on still images or short video clips of robots and participants are only exposed to these stimuli for small frames of time. The current literature on the uncanny valley does not thus allow a conclusion to be drawn about the persistence of uncanny feelings. This thesis addresses this gap in the body of knowledge by implementing interactive scenarios and performing a series of empirical investigations to study the development of people's uncanny feelings towards social robots over the course of one or several such interactive encounters with them. The findings suggest that novelty plays an important role in the feeling of uncanniness: Merely interacting with a robot for a brief period and thus giving human observers access to the robot's full behavioral stream lowers their rating of uncanny feelings towards the robot as compared to how they perceive it at first sight. Furthermore, repeated interactions with a robot can further lower uncanny impressions. These results contribute to the field of human-robot interaction, as they posit that increased exposure may result in limited feelings of uncanniness. This, in turn, potentially reduces the impact of uncanny feelings on long-term interactive encounters with robots. Instead of focusing on reducing the elicitation of uncanny first impressions, it may thus be more sustainable to further study how interactions can help people efficiently get to know a robot and overcome their initial reluctance towards it.

Keywords: Human-Robot Interaction, Uncanny Valley, Social Robotics, Human Perception of Robots, Multimodal Behavior

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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Congruency matters - How ambiguous gender cues increase a robot’s uncanniness

II Expressing Coherent Personality with Incremental Acquisition of Multimodal Behaviors

III ‘Can you say more about the location?’ The Development of a Pedagogical Reference Resolution Agent

IV The Attribution of Emotional State - How Embodiment Features and Social Traits Affect the Perception of an Artificial Agent

V Let Me Get To Know You Better - Can Interactions Help to Overcome Uncanny Feelings?

VI The Influence of Robot Personality on the Development of Uncanny Feelings towards a Social Robot
The Persistence of First Impressions: The Effect of Repeated Interactions on the Perception of a Social Robot

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Author Contributions

The following discusses the contribution by the individual authors to the papers included in this thesis.

I I designed the experiment with input given by the remaining authors of the paper, specifically Ginevra Castellano. I was solely responsible for collecting and analyzing the data. Implications of the results were then discussed with Ginevra Castellano before I wrote the manuscript. The remaining authors gave comments on the initial manuscript.

II The experimental work described in this paper was carried out while I was an intern at the Disney Research Lab Pittsburgh. Pedro Mota was responsible for implementing the personality-driven language model of the system, while I worked on the non-verbal behavior of the agent. Aida Amini developed the guessing game used in the experiment. The experiment was designed in close collaboration with Pedro Mota, James Kennedy, and Jill F. Lehman. Together with Pedro Mota, I was responsible for conducting the experiment and analyzing the results. The paper was written by Pedro Mota, Andrea Fox, James Kennedy, Jill F. Lehman, and myself in equal parts.

III This paper describes the development of a two-player game designed to enhance people’s geographic literacy. The initial idea for the domain was suggested by Ramesh Manuvinakurike. The dynamics of the game were further refined in close collaboration with Ramesh Manuvinakurike during a research visit at the University of Southern California. Input on the design was given by Kallirroi Georgila. I implemented the lab-based version of the game with technical help from Robert Keßler. The data collection was carried out by myself, with support from Ramesh Manuvinakurike (online version) and Giulia Perugia (lab-based version). Result analysis and discussion was carried out in collaboration between the authors. I took the lead on writing the paper with significant contributions by Ramesh Manuvinakurike, especially regarding the related work discussed in the paper.

IV I designed the experiment in collaboration with Giovana Varni and Isabelle Hupont with input given by the remaining authors. I was responsible for conducting the experiment, analyzing the collected data
and preparing the manuscript. The remaining authors provided comments and input specifically on the theoretical framework used in the paper.

V I designed and conducted the experiment, analyzed the results, and wrote the manuscript. Input on the final manuscript was given by Ginevra Castellano and Giulia Perugia.

VI The experiment was designed and conducted in collaboration with Giulia Perugia. Additional help during the data collection was provided by Alex Yuan Gao and Sita Vriend. I was responsible for the technical implementation, in particular the development and expression of the robot personalities, both for the verbal and non-verbal behavior. Giulia Perugia conducted the statistical analysis and took the lead on writing the result section of the manuscript. The other sections were written by myself, with input and edits from Giulia Perugia. Input on the final manuscript was provided by Ginevra Castellano.

VII I was primarily responsible for the experimental design and conduction of the data collection, with help of Giulia Perugia. The data was analyzed and discussed in collaboration with Giulia Perugia. The manuscript was written by Giulia Perugia and myself in equal parts. I took the lead on the related work, method and discussion section, while Giulia Perugia focused mostly on the results and visualizations. Input on the final manuscript was provided by Ginevra Castellano.
Publications Not Included in this Thesis

i  On the Role of Personality and Empathy in Human-Human, Human-Agent, and Human-Robot Mimicry
Giulia Perugia, Maike Paetzel and Ginevra Castellano. In The 12th International Conference on Social Robotics (ICSR), 2020.

ii  Nontrivial Lexical Convergence in a Geography-Themed Game

iii  RDG-Map: A Multimodal Corpus of Pedagogical Human-Agent Spoken Interactions

iv  Incremental Acquisition and Reuse of Multimodal Affective Behaviors in a Conversational Agent

v  Investigating the Influence of Embodiment on Facial Mimicry in HRI Using Computer Vision-Based Measures
Maike Paetzel, Giovanna Varni, Isabelle Hupont, Mohamed Chetouani, Christopher Peters and Ginevra Castellano. In IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2017.

vi  A Multidimensional Perspective on the Uncanny Valley Effect: Studying the Interplay Between a Robot’s Appearance and Interaction Strategy
vii Exploring the Link between Self-assessed Mimicry and Embodiment in HRI

viii The influence of appearance and interaction strategy of a social robot on the feeling of uncanniness in humans

ix Preliminary results from using a back-projected robot head in uncanny valley research
Maike Paetzel, Christopher Peters, Ingela Nyström and Ginevra Castellano. In Interactive Session, IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2016

x Towards incremental dialogue act segmentation in fast-paced interactive dialogue systems
Ramesh Manuvinakurike, Maike Paetzel, Cheng Qu, David Schlangen and David DeVault. In Special Interest Group on Discourse and Dialogue (SIGdial), 2016.

xi Effects of multimodal cues on childrens perception of uncanniness in a social robot
Contents

1 Introduction ................................................................................................ 11
  1.1 Thesis Objectives ............................................................................... 16
  1.2 Thesis Structure .................................................................................. 17

2 Empirical Evidence Behind the Uncanny Valley .................................... 19
  2.1 Methodology of the Meta-Review .................................................... 21
  2.2 Conceptual Differences in Uncanny Valley Related Studies ........... 21
      2.2.1 Robot Type .............................................................................. 21
      2.2.2 Stimulus Presentation .......................................................... 25
      2.2.3 Length of Exposure .............................................................. 25
      2.2.4 Interactivity of the Experience ............................................. 27
      2.2.5 Measuring the Uncanny ....................................................... 28
  2.3 Discussion ............................................................................................ 32

3 Hypotheses ................................................................................................. 35
  3.1 Comparability between Virtual and Co-Present Stimuli (H1) ........... 35
  3.2 The Effect of Interactivity in Exposures (H2, H3) ............................. 36
  3.3 Repeated Exposure and Interaction (H4, H5) .................................... 39

4 Methodology of the Empirical Investigations .......................................... 43
  4.1 Blended Embodiments to Study the Uncanny ................................. 43
      4.1.1 Morbidity and the Uncanny .................................................. 45
      4.1.2 Gender and the Uncanny ....................................................... 46
      4.1.3 Anthropomorphic Incongruence and the Uncanny ................ 47
      4.1.4 Conclusion ............................................................................ 48
  4.2 Scenarios ............................................................................................. 50
      4.2.1 Still Impressions .................................................................... 50
      4.2.2 Non-Interactive Impressions ............................................... 50
      4.2.3 Interaction-Based Impressions ............................................. 51
  4.3 Measures ............................................................................................. 54
      4.3.1 Questionnaires ....................................................................... 54
      4.3.2 Behavioral Measures ............................................................ 57

5 Results ........................................................................................................ 61
  5.1 Physical Presence (H1) ....................................................................... 61
  5.2 Interactive Scenarios (H2) ................................................................. 63
  5.3 Personality in Interactions (H3) ......................................................... 66
  5.4 Repeated Exposure (H4) ................................................................. 71
1. Introduction

In the field of human-agent interaction, few topics, if any, have received more attention than the *uncanny valley effect*. It was initially proposed in 1970 by the Japanese researcher Masahiro Mori and describes the relationship between an artificial agent’s human-likeness and people’s affinity with it [90]. According to Mori’s theory, the likability of an artificial agent generally grows proportionally with its level of human-likeness until the point where the agent’s appearance closely resembles that of a healthy human being. At this point, people’s feelings towards the agent drastically change, and they start perceiving it as uncanny. Only agents indistinguishable from humans can elicit positive feelings again. As depicted in Figure 1.1, Mori called this gap in an otherwise linear relationship between an agent’s human-likeness and the affinity towards it the *uncanny valley*.

In recent years, the uncanny valley has become popular both in mass media and in the scientific community and has been used to explain almost any kind of failure of computer-animated movies, game characters or any negative attitude towards human-like robots [153]. For example, when it was announced in summer 2020 that a Geminoid, a very human-like android robot, would play

![Figure 1.1. The uncanny valley as envisioned by Masahiro Mori [90].](image)
a main role in the new Hollywood movie “b,” speculations about uncanny feelings towards it rose immediately\(^2\). As Złotowski et al. noted, a narrative evolved from the ever-growing body of scientific studies and theories behind the uncanny valley, ascribing an enduring consequence to uncanny feelings, ultimately leading people to reject interacting with an agent altogether [153].

The assumption that uncanny feelings towards an agent will persist is, however, merely a hypothesis and not yet grounded in the existing body of research on the uncanny valley. Related work has almost solely focused on encounters with artificial agents lasting not more than a few seconds. Furthermore, participants in related experiments were often only exposed to images or video recordings of artificial agents, instead of getting a fully interactive experience. This might have limited people’s capacity to form an accurate representation of the agent’s abilities and behaviors. The aim of this thesis is thus to gain a better understanding of the role novelty plays in the perception of uncanniness and how uncanny feelings change over the course of interactions between a human and an artificial agent that go beyond first impressions.

The Importance of Co-Presence in Human-Robot Interaction (HRI)

While Mori’s original uncanny valley hypothesis focused on people’s affinity towards robotic platforms, many experiments have used computer-generated human-like agents to study it, as the appearance of the latter is more easy to manipulate. Related experiments on virtual humans have provided valuable insights into which elements in an agent’s appearance can cause uncanny feelings. This thesis, however, is concerned with Mori’s original hypothesis and focuses on the development of uncanny feelings towards robots. More specifically, we aim to further the understanding of the persistence of uncanny feelings in the context of human-robot interaction. Such interactive scenarios are, as Goodricht and Schultz note, “proximate rather than remote”, which means they require a co-present instead of a telepresent robot [41]. Experiments investigating uncanny feelings towards robotic platforms have, however, usually relied on still images or video recordings of the platform instead of physically present robots. To understand the impact of uncanny feelings on human-robot interaction, it is thus crucial to analyze how the proximate perception of co-present robots differs from virtual representations as used in the related work.

The Brevity of Experiences with Uncanny Agents

In social psychology, first impressions are usually defined as any encounter of less than five minutes in length [4]. However, exposure to the stimuli used in research related to the uncanny valley typically only lasts for a few seconds. Furthermore, people are merely provided with a thin slice, a “brief excerpt of expressive behavior sampled from the behavioral stream” [4], before their uncanny feeling towards an agent is measured. Thin slices are common in social

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1. Adapted from https://commons.wikimedia.org/wiki/File:Mori_Uncanny_Valley.svg
psychology to investigate first impressions and gain a better understanding of how much exposure to unacquainted humans is necessary to form an accurate opinion about them. It has been shown that thin slices are overall sufficient when judging whether someone constitutes a threat, is to be trusted, or could be a potential mate [3, 9, 143]; and they are often predictive of the future relationship that develops between two humans [56, 129]. Whether these findings from social psychology translate to the perception of artificial agents has not yet conclusively been studied, and there are notable differences between human-human and human-agent perception that might impact the transferability of findings between the two fields.

Forming Mental Models of Artificial Agents

In order to understand whether findings from social psychology on the accuracy of first impressions, specifically uncanny first impressions, translate to human-agent interaction, it is crucial to take a look at the process of forming impressions from perceptual cues. According to the Brunswik model of social perception (cf. Figure 1.2) [20], humans cannot directly observe the internal states of other human beings [139]. Instead, these states manifest as distal cues, which are external representations of internal states. For instance, if the human depicted in Figure 1.2 to the left is telling a story, her choice of wording, body language, and facial expressions, among others, would serve as distal cues and represent her emotions and personality. These external representations can, again, not be processed by the observer directly but need to be perceived as proximal cues. Based on the entirety of the available proximal cues, the observer forms a mental model of the speaker’s internal state. The accuracy of this model depends both on the ability of the observer to interpret the proximal cues (representation validity), as well as on the possibility of inferring the state of the distal stimulus from the proximal cues (ecological validity).

![Figure 1.2. A simplified version of the Brunswik model of social perception, adapted from [138]](image-url)
As humans, we constantly observe and interpret social signals from our interaction partners to form a mental model of them [139]. Throughout their life, people have numerous experiences of forming mental models of unacquainted humans, which helps them to gain a higher accuracy in inferring emotions and personality traits from the proximal cues they observe in others. When meeting an artificial agent, people’s interpretation of proximal cues may be less accurate due to the lack of experience in interacting with, and hence inferring emotional states and personality traits from, artificial agents in general and robots in particular. A survey conducted by the European Commission in 2012 found that only 12% of the European population had personal experience with a robot [119]. In a recent study we conducted on Amazon Mechanical Turk\(^3\) (cf. Section 5.4), 22.5% of participants living in the United States of America reported they currently or previously had a robot at home, and 23.8% had personal experience with one at their workplace. This number has likely increased since household robots like autonomous vacuum cleaners and lawn mowers became cheaper and more broadly available\(^4,5\). However, it shows that even simple and mechanical robots are still sparse in people’s day-to-day life. Moreover, interactions with commercially available robots like these are at the most simplistic and mechanical and might thus not be representative of encounters with more advanced and human-like robots that would potentially fall into the uncanny valley.

When forming first impressions of a robot, people may thus “rely on analogies with familiar, readily envisaged domains to build mental models” [95]. Further research is needed to understand whether humans, machines, or movie representations of robots are used as analogies to form an initial mental model of a robot and how this analogy is shaped by the robot’s physical appearance. Regardless of the exact mental model people have when interacting with a robot for the first time, due to their lack of exposure to robots, they likely need more proximal cues to predict the internal state of the robot. Hence, people’s judgement of an artificial agent or robot based on few proximal cues may be less accurate than their judgement of a human based on a comparable stream of cues. *Little prior experience with robots or artificial agents and limited access to proximal cues may thus lead to mental models that are not representative of the true nature and internal state of an agent.*

**Perceptual Mismatch as a Potential Cause of Uncanny Feelings**

A low ecological validity or representation validity can likely promote the formation of a perceptual mismatch, which, according a meta-review by Kätsyri et al., is the main source of uncanny feelings identified in empirical studies [60]. A perceptual mismatch occurs in case proximal cues observed in a stim-

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\(^3\)https://www.mturk.com/

\(^4\)https://techcrunch.com/2016/11/07/irobot-says-20-percent-of-the-worlds-vacuums-are-now-robots/

ulus are conflicting. Such a mismatch is, for example, elicited when observing the skin of an android robot. From the visual cues alone, it almost perfectly resembles the skin of a human being. Due to the lack of mental models of android robots, a person visually observing the very human-like looking android may rely on their mental model of a human being when forming expectations about the android. This could lead them to believe that the skin would feel like that of a healthy human as well. When touching the android, however, the observer would sense that the temperature of the skin is, in fact, quite cold, which conflicts with the expectation that was formed based on the visual cues, and a perceptual mismatch occurs.

If the observer was to interact with the robot for a longer period of time, their mental model of the robot would likely undergo a substantial update. This update would entail that in the next exposure to the robot, the same observer would rely less on the mental model of a human being and hence experience the perceptual mismatch less strongly. This is in line with findings from neuroscience, showing that the brain activity of human observers watching humans and mechanical-looking robots is predictable and in line with the appearance of the stimulus [111]. However, when observing movements of an android robot, patterns in people's brain activity do not resemble patterns when watching a mechanical looking robot but represent a larger prediction error when it comes to the nature of the stimulus. If people had more experience with artificial agents and robots, especially with very human-like ones, and were given access to a more complete set of proximal cues for a longer period of time, they might be able to overcome the initial perceptual mismatch and form a mental model of the robot with higher validity.

Long-Term Perception of Social Robots

Even though thin-slice impressions of other humans in general, particularly negative impressions, are overall accurate, they can still change when exposed to someone more often. Interestingly, repeated exposure (i.e., visual exposure without interaction) and repeated interaction (i.e., exposure explicitly allowing interactions) lead to a more favorable perception of another person [149]. Reis et al. formulated multiple hypotheses as to why this phenomenon occurs [104]. For example, they suggest that the more we interact with someone, the more possibilities we have to form favorable impressions. In addition, they also point out that repeated exposure increases perceptual fluency, which can in turn lead to a more favorable perception. This gives an interesting perspective on the notion that uncanny feelings may have a lasting impact on the long-term relationship between a human and an agent. Research on repeated exposure to artificial agents is sparse in general and even less common when it comes to the study of the uncanny valley. Złotoswki et al. were the first to design a study explicitly investigating the persistence of uncanny feelings [153]. While they found the robot’s likability to be mainly influenced by its attitude, the uncanny feelings in people who interacted with it for an hour were lower than
in those encountering it for the first time. We argue that, while an hour long interaction exceeds the usual exposure time in research related to the uncanny valley, this time period is still not representative of a long-term relationship between the human and the robot. Furthermore, the repeated measures in the experiment conducted by Złotoswki et al. did not refer to different encounters with the robot with multiple days of zero exposure in between but rather to multiple measurements taken within the same session of interaction.

How uncanny feelings develop over separate encounters with a robot is still an open question. Few researchers have conducted experiments on how long-term exposure to robots can change initial negative attitudes towards them. Bartneck et al. reported that people were less negative towards robots in general the more they had previously interacted with an Aibo robot [13]. Sundar et al. asked people about robots portrayed in movies they had watched and found that “sheer exposure to mediated portrayals of robots can have a positive effect on acceptance of robots” [128]. In line with Złotoswki et al., they also found the sympathy of the character portrayed and the level of human-likeness to have a significant influence on whether people’s judgement of the robot improved with more exposure to them. These first insights suggests that long-term exposure to a stimulus can be of importance when considering the impact of uncanny feelings on human-robot interaction.

1.1 Thesis Objectives

The arguments presented above point to three main shortcomings that currently limit our understanding of the persistence of uncanny first impressions:

1. Research on the uncanny valley is to a large extent based on still images or video recordings of a robot, while human-robot interaction relies on physically present robots [41]. A co-present robot allows for the observation of more proximal cues as compared to a still image or video recording of the same robot, which could alter uncanny feelings elicited by a co-present robot in comparison to virtual counterparts.

2. The related work has focused on non-interactive encounters to measure people’s uncanny feelings towards a robot, while human-robot interaction per definition requires interactivity. An interactive experience with a robot exposes people to more proximal cues, which could potentially change the uncanny feelings perceived at first sight.

3. Social robotics eventually envisions long-term relationships between a human and a robot, which are considered in danger by potentially enduring consequences of uncanny feelings [153]. It is hence important to study repeated exposure and repeated interaction explicitly to understand the persistence of uncanny feelings over time.

More access to proximal cues granted by allowing people to interact with a co-present robot could initially increase chances for a perceptual mismatch.
to occur and uncanny feelings to arise. In long-term interactions, however, it may help to form a mental model of the robot with a higher validity, which could consequently limit uncanny feelings elicited by a perceptual mismatch.

This thesis thus aims to provide empirical evidence that allow us to address the three gaps in the related work, as stated above, understand the effect of novelty in the uncanny, and consequently draw conclusions on whether uncanny feelings have a negative and enduring effect on the long-term relationship between a human and a robot.

1.2 Thesis Structure

In Chapter 2, this thesis first takes a critical look at the empirical evidence behind the uncanny valley theory with a specific focus on the methodology applied. We find that the existing body of work differs significantly in the type of stimulus and stimulus presentation, length of exposure, interactivity, and measures used to assess uncanny feelings. In addition, we discuss how the focus on very short exposures and non-interactive scenarios significantly limits the conclusions that can be drawn from previous studies when it comes to the impact of uncanny feelings on long-term human-robot interaction. Chapter 3 continues with providing an overview of the hypotheses derived from the related work that informed the development of the experiments included in this thesis.

To address the identified gaps in the literature and respond to our hypotheses, several scenarios were developed that allow us to study the development of uncanny feelings from people’s first encounter with a robot to repeated interaction sessions with it. To alter the uncanny feelings elicited by the robot, several initial experiments were conducted with the blended robot platform Furhat [1]. Despite its physical embodiment, Furhat’s appearance can easily be altered by applying different textures to its virtual face, enabling a manipulation of the uncanny feelings it elicits. The implications of using such a platform for research related to the uncanny valley as well as the interactive scenarios developed with it are further discussed in Chapter 4.

The empirical evidence collected as part of this thesis is summarized in Chapter 5. Our findings suggest that the practical implications of the knowledge gained from first impressions of uncanny robots as studied in the related work is limited when it comes to the long-term relationship between a human and a robot. We found co-presence of an agent to increase people’s uncanny feelings towards it. Since the majority of the related work has been conducted using still images or videos instead of a co-present agent, our results suggest that the severity of uncanny feelings elicited by robots in the related literature may have been under-estimated at times. However, further results presented in this thesis show that simply allowing people to interact with a robot for a brief period of time and thus exposing them to a larger variety of perceptual
cues lowers their rating of uncanny feelings towards the robot compared to how they perceived it at first sight. Finally, we show that both repeated exposure to and repeated interaction with a robot have a positive effect on people’s perception of the robot and significantly lower their discomfort with it.

Overall, the findings presented in this thesis suggest that novelty plays an important role in the feeling of uncanniness since an increase in familiarity, achieved by simply getting to know a robot, significantly reduced uncanny feelings elicited. These results have important implications for the human-robot interaction community, which are further discussed in Chapter 6. Instead of focusing on reducing the elicitation of uncanny feelings in the first place, it might be a more sustainable approach to design interactions that help people quickly get to know a robot and thus overcome the initial uncanny feelings towards it. The thesis thus concludes in Chapter 7 with the suggestion to emphasize research on design guidelines that can help people become familiar with a robot more effectively.
2. Empirical Evidence Behind the Uncanny Valley

In 1970, Masahiro Mori published his seminal *uncanny valley* hypothesis [90]. He noticed that the recent generation of prosthetic hands had become so realistic they could at first be mistaken for real hands. However, when looking at them more closely or even touching them, their artificial nature would become apparent and cause an uncanny feeling. He further noticed that this unsettling feeling became even stronger if the prosthetic hand could move. Based on these purely anecdotal observations, he hypothesized that artificial objects or machines designed to look human cause positive sentiments, up to a point where they can hardly be distinguished from real humans or human body parts. At this specific point, the sentiment towards the object or machine flips and becomes strongly negative. Mori called this drop in positive affect towards a human-like stimulus the uncanny valley and noted that a robot must truly be indistinguishable from a healthy human to elicit positive feelings again.

Mori himself hypothesized that the eerie feeling is the result of *self-preservation*, which is the brain’s attempt to protect us from danger. According to him, human-like machines could be unconsciously classified as proximal dangers, similar to members of different species or corpses [90]. Few empirical studies have further examined the relationship between human-like and morbid characters. Tinwell et al. found characters designed to resemble zombies in computer games to indeed elicit an uncanny feeling [133]. In their study, however, characters on the artificial end of the scale instead of the overly human-like characters elicited a similar negative affect. MacDorman conducted a study in which he asked participants to complete word fragment tasks related to death and uncanny feelings [73]. People showed more death- and uncanny-related associations after viewing an image of an android robot compared to a human, but only the difference in uncanny-related associations was significant. In a similar experiment, Koschate et al. found the difference in death-related associations to be significantly higher for an android in comparison to two less human-like robots [64]. More support can be found in studies on uncanny feelings towards virtual characters. McDonnell et al., for example, found virtual humans rendered to look ill to be rated as very unappealing and eliciting eerie feelings [83]. Later work by Tinwell et al. linked the detection of psychopathic traits in uncanny characters to the eerie feelings they elicit [134]. Due to the danger associated with psychopathic individuals, this too could be seen as evidence for the self-preservation hypothesis.
In a review conducted in 2015, Kätsyri et al. identified two different explanations for the uncanny valley effect: the *categorization ambiguity* and the *perceptual mismatch theory* [60]. According to the categorization ambiguity theory, uncanny feelings arise from ambiguous cues that lead to the inability to decide whether a stimulus is, in fact, artificial or human. The perceptual mismatch theory, on the contrary, suggests that any perceptual mismatch can cause uncanny feelings, even if the mismatch does not lead to doubt about the nature of the stimulus. Among the 125 articles included in their review, Kätsyri et al. found substantial evidence for the perceptual mismatch theory. Whether the categorization ambiguity theory could be an alternative explanation is, however, still controversial. Moore extended Feldman et al.’s Bayesian model of categorical perception, proposing the first mathematical model that could re-create the original uncanny valley curve [88]. Both Strait et al. and Mathur et al. recently carried out experiments specifically testing this hypothesis and came to different conclusions: Strait et al. found uncanny feelings to be both elicited by a perceptual mismatch caused by atypical features and by categorization ambiguity [122]. Although Mathur et al. found a categorization ambiguity within their set of 122 robot images, they could not confirm that these robots elicited uncanny feelings [81].

It is not just the theory behind the uncanny valley that is still controversial but also the general relation between anthropomorphism and likability. Bartneck et al. hypothesized that “[a]nthropomorphism and likability may be multi-dimensional constructs that cannot be projected into a two-dimensional space” [11]. Indeed, more evidence has been found lately suggesting that there may be several different related constructs that could be at play when investigating human-like agents. A human-like appearance can, for example, influence people’s perception of mind, agency, and autonomy of an agent – all of which have been linked to uncanny feelings [7, 43, 154]. In addition, likability and eeriness are subjective feelings that are not just influenced by the stimulus but also by interpersonal factors like a negative attitude towards robots [32], cultural background [93], or level of shyness [6].

Given the sheer number of theories and empirical investigations, one would assume the uncanny valley to have a substantial practical influence on the field of human-agent interaction. Indeed, as Złotowski et al. pointed out, uncanny feelings are often implicitly assumed to have a lasting impact on the relationship between the human and the uncanny agent [153]. In reality, however, the implications of agents eliciting uncanny feelings are rarely empirically investigated. This chapter will thus take a closer look at the methodology used to examine uncanny feelings with a focus on empirical evidence involving robotic agents, those present either physically or virtually. Based on these findings, it will be discussed how differences in the methodology can explain conflicting findings and what conclusions we can draw from the related work about the impact of uncanny feelings on human-robot interaction.
2.1 Methodology of the Meta-Review

To retrieve a list of related work on uncanny feelings in HRI, we performed a search of the terms “(uncanny valley) AND robot” in the search engines PubMed ($N = 25$), Scopus ($N = 218$), Web Of Science ($N = 182$), and Science Direct ($N = 235$), leading to a total set of 660 (490 unique) results, which was last updated in April 2020. This list was then manually screened and only papers fulfilling all of the following criteria were kept:

- The paper contains an empirical investigation.
- At least one of the stimuli involved in the empirical investigation is a real robot, an image of a real robot, a 3D model resembling a robot shape or the verbal description of a robot.
- The paper contains measures to investigate the uncanny valley.
- The paper is available in English.

Papers were then organized by experiment and results from multiple papers written about the same experiment were collapsed into a single entry. In the remainder of this section, the methodologies used in the resulting 91 unique experiments investigating uncanny feelings towards robots are presented.

2.2 Conceptual Differences in Uncanny Valley Related Studies

2.2.1 Robot Type

In Mori’s original graph depicting the uncanny valley, three types of stimuli were labelled [90]: (a) industrial robots that are low in human-likeness and low in affinity (cf. Figure 2.1 left), (b) human-like robots with a medium human-like appearance that elicit some level of positive affect (cf. Figure 2.1 center robots), and (c) healthy humans that score the maximum on both human-likeness and affinity. Robots located between (b) and (c) are called androids and resemble real humans almost perfectly (cf. Figure 2.1 right). If these

Figure 2.1. Robots with varying level of human-likeness. From left to right: (1) Industrial robot arm, (2) PR2, (3) Asimo, and (4) Sophia1.
robots are almost but not perfectly human, they should elicit strong uncanny feelings according to Mori’s theory.

Building realistic androids is technically challenging and the amount of android robots available for research purposes is hence limited. The most well-known set of android robots is designed and manufactured at the Hiroshi Ishiguro Laboratories (Advanced Telecommunications Research Institute, Japan) and called Geminoids. Geminoids are designed to be an identical twin of a real human model. Ishiguro’s lab currently owns a Geminoid HI-2 modelled after professor Hiroshi Ishiguro himself and a female Geminoid called Erica. In addition, researchers from Ishiguro’s lab created Geminoid HI-4 and Geminoid HI-5 (a head only version), Geminoid DK modelled after Danish professor Henrik Schärfe, as well as Geminoid F, all of which are currently used by other research groups. Hanson Robotics, a company located in Hong Kong, is the only commercial supplier of android robots. Their robots include the females Sophia (cf. Figure 2.1 right), Bina, and Nadine as well as the males Jules, Philip K. Dick, Diego-San, and Albert HUBO (modelled after Albert Einstein). David Hansson, the founder of Hansson Robotics, was also involved in creating the FACE android robot head in cooperation with the University of Pisa (Italy), and Ibn Sina in cooperation with the United Arab Emirates University. Few additional research groups have built their own android robots, including Saya (Tokyo University, Japan), HRP-4c (National Institute of Advanced Industrial Science and Technology, Japan), EveR Model 1 to 4 (Korea Institute of Industrial Technology, South Korea), the Actroid family ReplieeQ1 and Q2, as well as Actroid M and F (Osaka University, Japan).

Experiments directly comparing the current generation of androids to other classes of robots and humans have consistently shown androids to elicit the most eerie feelings [51, 52, 71, 74, 91, 105, 122]. Strait et al. even found comments written under YouTube videos about android robots to be significantly less positive as compared to the comments on videos of more mechanical robots [121]. These findings suggest that current androids do indeed fall into the uncanny valley. Rosenthal-von der Pütten et al., however, suggested that the strength of eerie feelings reported towards androids could be influenced by the choice of the other stimuli they are compared with. Specifically, they found android robots to be rated comparably low in eeriness when a set of artificial humans (humans with extreme plastic surgery) was included [109]. In addition, multiple studies have found not all androids to elicit the same strength of uncanny feelings. Reuten et al., for example, found Saya to elicit significantly more uncanny feelings than Albert HUBO, Diego-San, and Sophia [105]. Lischetzke et al. created androids by blending human and robot faces. While these blends did evoke more uncanny feelings than the original robots and hu-
mans, they found the depth of uncanny feelings to differ significantly between the three different blended android stimuli [71]. Rosenthal-von der Pütten and Krämer investigated 40 images of robots, including four android robots [107]. While all of the androids were rated as extremely human-like, Geminoid DK and HRP-4c were considered fairly likable, while Geminoid HI-1 and Ibn Sina elicited threatening feelings.

The reasons behind the different levels of uncanny feelings elicited by different android robots has not yet been thoroughly investigated. One factor could be the exact level of humanness the different androids represent. Nakane et al. asked people to classify 16 images, 8 showing android robots and 8 depicting humans [91]. They found androids to be more likely classified as humans (57%) than as android robots (43%). Although they did not discuss whether some androids were misclassified more frequently, their findings suggest that people may actually mistake androids for humans when presented with a still image. The potential for misclassification could depend on the level of detail shown in each image. Robots and humans in the study by Nakane et al. were depicted as close-ups of the face only. In other research by Rosenthal-von der Pütten and Krämer, full-body images were used [107]. It may be possible that the posture of the robots, the clothing, or the hairstyle showed more signs of artificiality than the facial features alone, which decreased the potential for misclassification.

Lee et al. published one of the few qualitative studies to gain more insights into conscious thought processes behind people’s aversion to robots [66]. In their study, participants justified their negative feelings towards android robots by citing the unpleasant facial expressions shown by them. Their high level of human-likeness was not mentioned by participants. While this could indeed point towards a low influence of human-likeness, it could also mean participants were consciously not aware of the impact it had on them. Interestingly, one of the participants in their study commented on the racial background of the Geminoid robot: “When I say he is a bit sinister, it’s because he is Asian.” While this was only brought up by one person, it could shed new light on the findings reported by Rosenthal-von der Pütten and Krämer [107]. The two android robots that were reported to elicit threatening feelings resembled a Japanese and an Arabic person, while the Geminoid DK robot can be assumed to have a similar racial background as their sample population of German university students. The HRP-4c, however, has Japanese features as well, but these are less prominent compared to the Geminoid HI-1 robot. Some researchers have also found evidence that male characters elicit more uncanny feelings than female characters [44, 134], which could be another explanation for the more positive ratings towards the only female Geminoid in their set.

In contrast to Mori’s original hypothesis, related work has also found mechanical robots to elicit uncanny feelings. Rosenthal-von der Pütten and Krämer, for example, found not just androids but a class of mechanical robots they describe as tall and bulky to be considered threatening [107]. Interestingly,
eight of the eleven robots in the threatening but mechanical category could be classified as human-like when judging their body proportions and bipedal locomotion abilities. Applying Mori’s uncanny valley model, they should have elicited moderately positive feelings. Łupkowski and Gierszewska found the highest level of discomfort to be ascribed to two of the very mechanical computer-generated robots and not towards the more human-like ones [72]. Similarly, Stroessner reported more mechanical robots to be associated with a higher discomfort [126]. This contradicts findings by Ho and MacDorman, for example, who found purely mechanical robots to be rated low on eeriness [51]. An explanation for the diverse findings on robots with less human-like features could be the specific type of mechanical robots used by Ho and MacDorman in comparison to Rosenthal-von der Pütten and Krämer or Strasser. The robot images in the study by Ho and MacDorman were comparably small and could almost be considered toy-like, a class of robots that consistently scored very high when it comes to likability [107]. Bartneck et al. even found toy-like robots to be appreciated more than images of real humans, which brought them to the suggestion that the uncanny valley could be an uncanny cliff and the goal of designing robots to be as human-like as possible may be the wrong approach when aiming for likability [10].

Not all empirical investigations have included a broad variety of robotic stimuli. In fact, the subset of robots used in the related work is often small and varies greatly between experiments. Quadflieg et al., for example, created a set of scenarios that either depicted two humans or a human and a human-sized NAO robot to investigate uncanny feelings [100]. This choice of stimuli is interesting, given that the NAO robot was categorized as toy-like and likable by Rosenthal-von der Pütten and Krämer [107]. Destephe et al. used a WABIAN-2R robot in their experiments, which is of actual human size and includes many clearly visible mechanical features [32, 33]. While this robot may cause some threatening feelings, it would still not be categorized as overly human-like according to Mori’s original graph. Whether Destephe et al.’s findings about the uncanny feelings elicited by different walking trajectories in their WABIAN-2R robot would translate to toy-like robots or androids was not discussed.

To summarize, many experiments in the research field of the uncanny valley have only deployed a small subset of robots to study uncanny feelings. The choice of the specific platform was not always grounded in the robot’s level of human-likeness and related literature investigating uncanny feelings towards comparable types of robots. One future approach to understanding differences in perception between the various robots eliciting uncanny feelings could be including further measures like the EmCorp-Scale developed by Hoffmann et al., which measures “bodily-related perceptions of the embodiment” [54].
2.2.2 Stimulus Presentation

The experiments not only deviate in the type of robot stimulus, but also differ in the way the stimulus was presented. As depicted in Figure 2.2, four main groups of stimuli presentation can be found in the 91 experimental studies selected for this analysis. Almost half of the experiments, \( N = 39 \) (43.3%), used images as a stimulus to elicit uncanny feelings. This stimulus presentation can be characterized by only providing a unimodal impression of the robot based on its appearance alone. The second largest group, \( N = 30 \) (33.3%), consists of experiments in which video recordings of a robot were utilized. Videos allow people to form a multimodal impression of the robot: The visual judgement can be enriched by behavioral cues, including movements of the robot and, in some cases, speech or other auditory cues. Only \( N = 18 \) (20%) studies involved a physically co-present robot. The exact presentation of co-present robots varied and included both unimodal and multimodal impressions and could be interactive as well as purely observational. Of the experiments that involved a physically co-present robot, \( N = 13 \) (72.2%) were conducted in a laboratory environment. The four studies that took their robotic stimuli out in the wild either took place at a museum [14, 78], a science exposition [151], or a cafe [108]. In one paper, the location of the study could not be determined [132]. The final and smallest group of stimuli presentations consists of \( N = 3 \) papers (3.3%) in which only verbal descriptions and no visual imagery were presented.

2.2.3 Length of Exposure

Another factor that varied between experimental designs was the time people were exposed to the robots. In the following, patterns in the length of exposure are examined separately for the three different types of stimuli that included some form of visual depiction of a robot.

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Figure 2.2. Distribution of stimulus presentation types across the 91 experiments included in the meta-review.

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2One study was excluded from the calculation since the exact type of stimulus could not be determined from the paper.
Robot Images
In the majority of studies that utilized still images of robots, $N = 24$ (61.5%), the time participants were exposed to the stimuli was not controlled. Among studies that left the time of exposure to the control of participants, only one paper reported how long participants chose to look at the stimuli. In their experiment, MacDorman report participants to have spent 2 - 262 seconds at the page displaying the stimulus, with an average of 21.9 seconds and a median of 12 seconds [73]. Since the study was conducted online, it can be assumed that participants who spent an extensive amount of time on the page probably were not attentive to the stimulus for the entire time that was reported. Whether the time spent on the stimulus page influenced people’s responses to the questionnaires was not reported. In an additional three experiments, the exact time of exposure was not controlled, but part of the dependent variables and participants were instructed to respond as fast as possible [23, 76, 81].

If the exposure time was explicitly controlled, it was usually below the median of 12 seconds that was reported by MacDorman. The shortest time period was used by Ferrey et al., who exposed participants for only 400ms to each image [38]. Most common were exposure times of 2 - 5 seconds, as applied by Ratajczyk et al. [102], Wang and Quadflieg [141], Strait and Scheutz [123], Nakane et al. [91], Rosenthal-von der Pütten et al. [109], and Reuten et al. [105]. Strait et al. have often followed an intermediate approach in their latest experimental designs: Participants were exposed to a stimulus for at least 6 seconds, after which they could decide to skip and move on to the next image. If they decided not to skip, the stimulus would automatically switch after 12 seconds [124, 125, 122]. The longest exposure time using still images that was explicitly controlled for was 60 seconds [131].

Robot Videos
For the 22 papers that reported the length of the video clips used in their experiments, the clips were 2 - 887 seconds long. In 18 of the experiments, the duration of all the video stimuli was less than or equal to 60 seconds, and in 9 studies, the duration was less than or equal to 12 seconds. For $N = 8$ (26.7%), the length of the video clips was not reported.

With just 2 seconds in length, the shortest video clips were used by Urgen et al. [137], Saygin et al. [110], and Piwek et al. [97]. Both Urgen et al. and Saygin et al. used the same set of video clips in which a Repliee Q2 and the human after which the Repliee Q2 was modelled performed a set of actions, like drinking water or grasping an object [110, 137]. In the video clips by Piwek et al., it was not just the appearance of the 3D generated robot that was altered, but also the smoothness of the motion it used to knock on a door [97].

\[^{3}\text{Papers that did not mention the exposure time explicitly were assumed to have not controlled for the exposure time.}\]
On the other extreme end of the scale are the stimuli that last more than 60 seconds. Strait et al. used 24 videos published on YouTube that varied in length between 54 and 272 seconds and studied the comments that were posted under the videos [121]. Each of the videos featured only one specific robot. A similar approach was taken by Yu, who analyzed YouTube comments under two videos about a robot hotel [148]. The two videos were 93 and 887 seconds in length and both featured a variety of different robots deployed in the hotel. Złotowski et al. only included one video of 240 seconds length featuring different robots, which was accompanied by different narratives between conditions [154]. Yogeeswaran et al. produced four documentary-style videos of 240 seconds each, which featured the Geminoid HI-2 or a Nao robot [146].

The experiment conducted by Strait et al. [121] is only one of several that compares people’s perception based on videos of different length. Destephe et al. included clips that displayed robot’s walking behavior for 5 - 10 seconds [32]. Participants could, however, replay the clips. Schweinberger et al. based their study on short YouTube clips, 22 - 33 seconds in length [112]. While Strait et al. found the length of the clips to not be a confounding factor in their experiment [121], both Destephe et al. and Schweinberger et al. do not discuss whether the different exposure times influenced people’s perception of the robots. Ho and MacDorman used short video clips of 6 - 12 seconds and 15 - 30 seconds in several of their studies. The video clips were, however, played in a loop so that the different length of the videos was less likely to influence the ratings the robots received [51, 52, 53].

Co-Present Robots
The authors of only 6 of the studies in which a co-present robot was involved included the time of exposure or interaction. The shortest time was reported in the experiment conducted by Silvera-Tawil and Garbutt, who exposed people for only 5 seconds to an Actroid F robot [116]. Mara et al. and Bartneck et al. had participants engage in an approximately 5-minute long interview sessions with a Geminoid HI-1 [78] or a Telenoid [11]. Yamamoto et al. asked children to play in the same space as a Keepon robot for a maximum of 10 minutes [145]. Children could decide to leave the space earlier if they wished. Zhang et al. conducted an experiment in which adults taught the android robot Nadine image recognition for about 15 minutes [150]. The longest interaction is reported by Zlotsowski et al. [153]. In their study, participants had three consecutive interaction sessions with a Geminoid HI-2 or a Robovie R2, which lasted for about an hour in total.

2.2.4 Interactivity of the Experience
In only $N = 16$ (17.6%) of the experimental studies did participants get the chance to interact with the robot. In all of the 16 studies involving real interactions, the robot was physically co-present. The largest group within the
interactive scenarios includes interview-like verbal communication between a human and a robot. Some involved the robot interviewing the human conversation partner [11, 113, 153]; in other studies, the robot was the one being interviewed [14, 108]. In the experiments conducted by Koschate et al. [64] and Yomamoto et al. [145], the robot was limited to non-verbal reactions. Only 4 studies involved a task-based interaction, which again varied significantly in the specific design of the task: Zhang et al. implemented a teaching scenario in which the human was asked to show the robot how to recognize images [150]. The experiment designed by Castro-González et al. involved humans playing a tic-tac-toe game with a Baxter robot [24], while Williams et al. asked a human to complete a search-and-rescue mission with two robots [142]. The work by Broadbent et al. was situated in the medical context and the robot assisted people with taking their blood pressure [19]. In the papers by Marcos et al. [79], Zia et al. [151], and Tay et al. [132], the type of interactive scenario was not reported in detail.

Several important differences can be observed between the interactive scenarios. First, the interactive modalities differ. Keepon, for example, can produce sounds and perform limited full-body motions but does not talk. Android robots like Jules or the Geminoid HI-1, on the contrary, can perform human-like facial expressions and are usually equipped with human-like voice synthesizers. In some of the experiments, the robot engaged verbally with the participants, in others it was restricted to non-verbal behavior. Second, the nature of the task was either cooperative (e.g., in the search-and-rescue mission) or competitive (e.g., in the tic-tac-toe game). Finally, the interpersonal dynamics between or the social role of the human and the robot differed. Złotowski et al., for example, introduced the Geminoid HI-2 and Robovie R2 as interviewers conducting a job interview with the human applicants [153]. In this scenario, the robot had more power than the human and its social role was thus superior. The human and the robot also pursued different goals in their interaction; one was trying to get a job, while the other aimed to find the best candidate for a job. This classifies the task as non-cooperative. The tic-tac-toe game shares the non-cooperative element with the interview scenario, but the two players were socially placed in an equal position [24]. The picture learning task, on the contrary, is a cooperative task in which the human played the role of the teacher and the robot acted as the learner. Similarly, assisting with measuring blood pressure is a cooperative task; but in this scenario, roles are reversed and the robot acted as the teacher and the human as the learner.

2.2.5 Measuring the Uncanny

$N = 73$ (80.2%) of experiments investigating the uncanny valley solely or partially measured the degree of uncanny feelings based on self-reports. Self-reported measures involve asking people to rate their feelings towards a robot
on a scale, (semi-)structured interviews about people’s feelings, as well as subjective comments posted under online videos. Beyond self-reports, other measures like behavior observation, gaze patterns, EEG, or fMRI recordings were used to assess people’s feelings towards the robot stimuli. \( N = 26 \) (28.6\%) of the papers involved such measures.

**Self-Report of Uncanny Feelings Based on Questionnaires**

In his original paper, Mori used the Japanese term *shinwakan* to describe people’s feelings towards increasingly human-like entities [90], which cannot directly be translated into English [11, 51]. In 2009, Bartneck et al. proposed *likability* to be a more suitable translation as compared to the more commonly used term, *familiarity*, at the time [11]. Ho and MacDorman, in comparison, argued the term to be a blend between the feelings of *familiarity*, *rapport*, and *comfort* [51]. In the officially authorized translation of Mori’s original paper published in 2012, the broader term *affinity* was established, and negative feelings towards human-like entities were described as *uncanny* or *eerie* [90].

To date, there is no standard questionnaire to measure affinity or uncanny feelings towards robots. Indeed, the exact factors used to construct the several scales developed to capture the uncanniness of an agent show little overlap. The first questionnaire that was adopted by multiple researchers in the community was the Godspeed questionnaire by Bartneck et al. [12]. Two of the scales are of specific interest when reporting uncanny feelings. Likability consists of the items *dislike-like*, *unfriendly-friendly*, *unkind-kind*, *unpleasant-pleasant* as well as *awful-nice*. Assessment of the perceived safety of a robot is based on the terms *anxious-relaxed*, *calm-agitated*, and *quiescent-surprised*. Five of the 91 papers included in this meta-analysis used the Godspeed questionnaire [26, 136, 148, 150, 153]\(^4\).

Just a year after the Godspeed questionnaire was published, Ho and MacDorman reported the perceived safety scale to only have a low reliability and a low factor loading for *quiescent-surprised*. While the likability scale was found to be reliable, it was highly correlated with anthropomorphism, which suggests that they were measuring the same, instead of distinct, perceptual concepts [51]. Ho and MacDorman then developed a new questionnaire that they further revised in 2017 [52]. This questionnaire consists of the scales *humanness*, *eeriness*, and *attractiveness*. Eeriness is constructed based on nine factors: *predictable-eerie*, *dull-freaky*, *ordinary-supernatural*, *boring-shocking*, *uninspiring-spinetingling*, *predictable-thrilling*, *bland-uncanny*, *unemotional-hairraising*, and *plain-weird* [52]. They argued that, unlike the Godspeed questionnaire, their newly developed eeriness scale properly captured the uncanny feeling described by Mori. However, apart from experi-

\(^4\)This count excludes papers that used the Godspeed questionnaire simply in comparison to a different, newly developed scale.
ments conducted by Ho or MacDorman themselves, only $N = 10$ of the other studies applied their scale [32, 33, 64, 71, 77, 78, 86, 123, 127, 153].

In 2012, Gray and Wegner introduced a much shorter questionnaire measuring uncanny feelings, consisting of only three different factors: creepy, uneasy, and unnerved [43]. This questionnaire was applied in four other experiments conducted by two different research groups [5, 6, 7, 62]. Recently, Carpinella et al. developed the Robotic Social Attributes Scale (RoSAS) [22]. Their questionnaire includes the scales competence, warmth, and discomfort, where warmth is measured using the factors happy, feeling, social, organic, compassionate, and emotional and discomfort is composed of scary, strange, awkward, dangerous, awful, and aggressive.

From the four questionnaires that were proposed as measures for the uncanny valley, only the Godspeed questionnaire and the RoSAS scale overlap in the specific perceptual dimensions included. However, even these two only have the item awful in common. All other questionnaires are entirely distinct in their factors and their relation to each other has, to the best of our knowledge, not been discussed. Taking all 91 papers into account, the factors that were used to study uncanny feelings most often were eerie ($N = 26$), likable ($N = 22$), creepy ($N = 14$), attractive ($N = 7$), uncanny ($N = 7$), and familiar ($N = 7$), which mostly overlap with the factors included in the questionnaires above. The factors less commonly used in the related work to measure uncanny feelings ($N \leq 7$) are visualized in Figure 2.3. In some papers,
these concepts were measured using one of the four questionnaires introduced above. In many, however, authors only used one instead of multiple scales per related feeling. For example, instead of measuring eeriness using nine scales as in the questionnaire developed by Ho and MacDorman, participants were often only asked to rate how eerie the robot was perceived to be. While most experiments at least included multiple questions consisting of both positive and negative terms, some only used scales with negatively connoted terms, like eerie or threatening [91, 98, 122], and others only involved positive terms, such as likable or attractive [38, 80, 140]. The choice of the scale could potentially confound findings of these studies, since the wording of terms could implicitly bias people in their ratings.

In addition to taking a closer look at the exact perceptual concepts related to the uncanny valley, it is worth examining whether participants were always able to relate to the perceptual dimension in question. Especially when using non-native English speakers as participants, it is likely that not all of them were familiar with terms like uncanny or eerie. A lack of understanding of these terms could potentially make people’s ratings unreliable if no definition was provided, and only Poliakoff et al. reported that their questionnaire included an explicit definition of the term eeriness. They defined eeriness as “mysterious, strange, or unexpected as to send a chill up the spine” [98]. In addition to providing official definitions, translating questionnaires could be another approach to ensure people could personally relate to the terminology used. However, only Bartneck et al. provided official translations of the Godspeed questionnaire into several other languages [12]. In most studies included in this meta-review, the English version of questionnaires was utilized regardless of participant’s native language.

**Measures Beyond Questionnaires**

Few experiments took participant’s behavior into account as an additional measure to judge responses to uncanny stimuli. These behavioral measures include the response time when performing classification tasks [23, 70, 91], task success [63], or the treatment of the agent in tasks like a one-shot investment game [80]. Strait et al. allowed participants to skip agent stimuli after they had been exposed to them for at least 6 seconds, and they measured the termination frequency in addition to people’s rating of each robot [124, 125, 122].

In some experiments, questionnaires could not be applied to measure people’s feelings towards the robot stimulus. Rosenthal-von der Pütten et al. were interested in studying natural reactions to a Geminoid HI-1 robot placed in a cafe [108]. They thus recorded the space the Geminoid robot was placed in and coded how long people spend in that area in general, how close they got to the robot, the amount of time they paid attention to the robot, how long they talked to the robot, and any attempts to test the Geminoid HI-1’s capabilities and reactions. The age of participants is another factor leading researchers to choose behavioral measures over interviews and questionnaires. Yamamoto et
al. performed their study on two to three-year-old children, who were deemed too young to be interviewed about their experience [145]. Instead, researchers manually coded how often they looked at the Keepon robot and how much time they spent in the area close to the robot, the area containing other toys, and the area their parents were located in.

While Yamamoto et al. manually coded the time children gazed at the robot, others have applied specific eye-trackers both in studies on infants and adults. In these studies, the fixation time on the stimulus in comparison to the time looking away from it [114], as well as the direction of gaze when looking away was analyzed [113]. Smith and Wiese designed a task in which participants first looked at a target and were then instructed to move their gaze to a different target as fast as possible [118]. They then studied the delay in redirecting participants gaze to the new target. In other studies, several regions of interest were defined and the time spent gazing at each of the regions was measured [82, 116, 125, 131]. Eyetrackers not only enable studying gaze direction but also pupil dilation. This was discussed by Reuten et al. as a potential measure of uncanny feelings [105]. The last set of measures that was used to examine uncanny feelings utilizes brain activity analysis based on EEG [137] and fMRI readings [58, 109, 110, 141].

2.3 Discussion

Several methodological shortcomings become apparent in the related work on the uncanny valley presented in this chapter, which makes it difficult to draw conclusions that go beyond the specific setting used in an individual experiment. First of all, it seems that the debate around the official translation of the term shinwakan is reflected in the variety of different measures applied to investigate the uncanny valley. It remains unclear, for example, whether the dislike of an agent is comparable to the feeling of eeriness. Ho et al. studied the feeling of uncanniness in relation to other feelings like fear and disgust. They came to the conclusion that “the uncanny valley may not be a single phenomenon to be explained by a single theory but rather a nexus of phenomena with disparate causes” [53]. Especially the kind of uncanny feelings ascribed to both very human-like and very mechanical robots may differ. While large and bulky mechanical robots could cause a legitimate fear of physical harm, androids and other very human-like robots may elicit a feeling closer to the fear of the unknown or disgust. This theory can be used to explain some of the conflicting findings in the related work. However, more experiments explicitly studying the relation between the different factors used to investigate uncanny feelings are necessary to determine whether this theory holds.

In addition to understanding the relationship between different questionnaires used to investigate uncanny feelings, it is important to consider individual differences when rating robots. More specifically, we need to understand
whether participants can personally relate to the terms that are provided to them in a questionnaire. The words “uncanny” and “eerie”, for example, may not be known to non-native speakers. Even when providing a definition of the terms, it might be difficult for them to relate to the type of feeling on a personal level. Besides the language problem, people also have different experiences when rating uncanny feelings. Participants used to uncanny characters in movies or computer games may rate a robot very differently from someone who is rarely exposed to such characters. Only in a few studies was the concept of familiarity or previous experience with robots explicitly included, which makes it difficult to judge its importance when rating uncanny feelings towards a stimulus. In addition, further research is required that takes other interpersonal differences into account to better understand who is specifically susceptible to uncanny feelings.

Even if the exact same robot was involved in different experiments, the presentation of the stimulus has likely influenced people’s rating. For example, people could potentially mistake an android for a human if only provided with an image of the robot. Such a mistake is still possible when being exposed to a co-present robot if some features of the robot are covered and the exposure time is very brief [116]. Once people get to interact with the android, however, its artificial nature will become apparent, at least for the current generation of androids. This has implications for both explanatory theories behind the uncanny valley: While people may have insecurity about the categorization of an android when seeing an image, this likely becomes resolved when they are given access to the full behavioral stream of the robot. On the contrary, the perceptual mismatch encountered may increase the more modalities people are exposed to, which could increase uncanny feelings for videos and co-present robots in comparison to images in the short term. The relation between people’s feelings towards still images, short videos, and co-present robots is still understudied and makes it difficult to compare experiments involving different modalities of presentation.

The number of proximal cues provided and the length of exposure plays a further role when judging stimuli [21]. In social psychology, first impressions or thin slices are usually defined as those impressions that are based on an exposure of five minutes or less [4]. Only three of the experiments studying uncanny feelings towards robots have reported exposure periods that exceed those of first impressions. The longest interaction was reported by Złotowski et al. [153]. In their study, participants completed three interactive tasks with a robot that lasted an hour in total. Even though they divided their exposure into three sessions with a short break in between, the time of zero exposure was too short to consider the three sessions as repeated exposure or long-term interaction with a robot.

One implicit assumption made about the effect of uncanny feelings is that it leads to future avoidance of a robot [153]. In other words, is is assumed that people do not give a robot a second chance after it made an uncanny first
impression. Strait et al., however, have found that uncanny impressions do not lead to more avoidance in short-term exposure [124, 125]. People decided to terminate their exposure to both uncanny agents as well as mechanical robots and humans with equal frequency. However, uncanny agents were avoided more strongly because people felt unnerved, while the others were skipped due to boredom. Shin et al. found the perception of eeriness of a virtual character based on a 20-seconds long video to be significantly correlated with people rejecting a friend request of that specific character [115]. Bing and Michael found that people rated a virtual agent they had seen as more human-like and pleasant than unfamiliar agents and they would rather pick an agent they have met before for a future experience even if the shared experience with the agent in the past was stressful [16]. To understand whether the (lack of) avoidance in short encounters is representative of longer and repeated exposures as well, further investigation is necessary. With an hour being the longest time of exposure that was studied in the related work and no experiments investigating the effect of repeated exposure or repeated interaction, it is impossible to draw conclusions about the impact uncanny feelings have beyond first impressions. Moreover, with the lack of studies allowing for an interaction between the human rater and the robot, even the effect of uncanny feelings on short-term human-robot interaction is unclear.
3. Hypotheses

A major shortcoming of the related work as discussed in the previous section is that the body of empirical evidence does not allow drawing conclusions regarding the persistence of the uncanny valley effect and its impact on human-robot interaction. In this thesis, the main objective is to study whether people’s first impression as traditionally measured in the related work is predictive of future interpersonal relationships with a robot. By explicitly considering the effect that novelty may play in the feeling of uncanniness, the goal is to better understand the impact of these feelings on long-term human-robot interaction. Three main focus areas were identified based on the gaps in the literature as discussed in Chapter 2. The related hypotheses informing the studies included in this thesis are introduced in the remainder of this chapter.

3.1 Comparability between Virtual and Co-Present Stimuli (H1)

Since only 20% of empirical investigations on the uncanny valley effect exposed people to physically present robots, uncanny feelings towards co-present robots can be considered understudied. One aim of this thesis is to further understand whether the physical co-presence of a robotic stimulus influences people’s perception of it. In his meta-review on physical presence, Li concluded that a physically present robot is overall rated more favorably than virtual and telepresent robots [69]. In four out of five studies specifically investigating people’s rating of the robot’s likability and social attraction, a positive influence of the physical presence was reported. In the remaining paper, no significant difference was found between the different conditions. Similarly, all four experiments investigating enjoyment found a positive influence of physical presence on people’s rating of the robot. None of the papers under investigation included a particularly uncanny robot or measures tailored towards the robot’s uncanniness. Whether co-present robots generally elicit stronger feelings than their virtual counterparts or whether they only elicit stronger positive affect has not been conclusively investigated yet. Based on knowledge from the related work, the relation between uncanny feelings towards virtual representations and physically co-present robots could potentially unfold in two ways: If co-present robots generally invoke more positive feelings, uncanniness could be more pronounced when exposed to a virtual version of the robot embodiment. However, if a robot’s co-presence generally
amplifies feelings, the uncanny sensation elicited by a co-present robot should exceed those elicited by their virtual counterparts. Mori’s original hypothesis that uncanny feelings are a response to protect the body from proximal danger supports a potential increase in uncanny feelings towards co-present robots [90]. Moreover, this would be in line with the perceptual mismatch theory [60], since a co-present robot should allow for the observation of a broader variety of distal cues potentially causing such perceptual mismatch.

**Hypothesis 1 (H1):**
Uncanny feelings towards a physically co-present robot exceed those towards a virtually present counterpart.

To confirm this hypothesis, it is crucial to use a robotic platform that can easily be presented as a physically co-present and virtual embodiment. A type of platform that was deemed particularly suitable for this is called a blended embodiment. Blended embodiments are a combination of a physical body and a virtual face texture. Virtual representations of this embodiment can be created by both taking a video recording of the physically co-present robot and by applying the same face texture to a virtual human – an approach that is further discussed in Section 4.1.

### 3.2 The Effect of Interactivity in Exposures (H2, H3)

82.4% of encounters with potentially uncanny robots were characterized based on a few seconds of exposure that only involved the human passively observing the robot without a chance to interact with it. If people’s first impression is accurate and predictive of their future relationship with a robot, their initial uncanny feelings towards it should not change after getting to know it better. Carney et al. reviewed empirical evidence on the effect of exposure time on the accuracy of people’s first impression of another human [21]. They found that the exposure time was of significant influence when judging positive affect but did not influence the rating of negative affect. Negative affect, however, can correspond to a variety of different feelings, from simple dislike to a life-threatening fear. While uncanny feelings fall under the umbrella of negative feelings, they have important characteristics that potentially decrease their durability. Pollick speculated that the choice of uncanny valley to translate the Japanese term *bukimi no tani* was most likely based on Sigmund Freud’s “Das Unheimliche” (English: The Uncanny) [99]. Freud argues that the German word *unheimlich* originated as the opposite of the word *heimlich*. While the most well-known meaning of the word *heimlich* translates to secretive, it originally referred to a feeling of familiarity. According to Freud, unfamiliarity is
hence a core ingredient in the feeling of uncanny. Encounters in real life that cause uncanny feelings are those that make us question our common beliefs about reality. The thought of the resurrection of a dead person, for example, is contrary to the scientific body of knowledge and would thus, if we were to witness such an event, cause an uncanny feeling. If resurrection were to become a familiar event, however, uncanniness could fade [40]. Consequently, if unfamiliarity was core to uncanny feelings towards robots, it can be hypothesized that the unfamiliarity with a certain type of stimulus might play a significant role in the development of uncanny feelings. If this hypothesis holds, we should see a decrease in people’s eerie feelings towards a robot after familiarity with it increases.

Carney et al. further found that people’s judgement was more accurate when their impression was not based on the very first encounter, but on the third minute of a 5-minute long conversation between strangers [21]. They suggested that encounters in which people begin to learn something about the other may be more meaningful to build accurate impressions. Video samples included in the related work on uncanny feelings towards robots did not usually include a similar sample from the behavioral stream. Instead, the videos focused on the robot’s abilities, like walking [32, 33], grasping [82, 110, 137], or knocking on a door [97]. While these may give a more accurate impression of the robot’s physical abilities in comparison to still images, it seems unlikely that relevant information predictive of interpersonal relationships can be drawn from these samples. One way of increasing familiarity meaningful to the decrease of uncanny feelings could thus be to give people a true thin-slice experience with a robot. While access to the robot’s full behavioral stream could initially increase the potential for a perceptual mismatch and uncanny feelings associated with it [111], we hypothesize that an interaction of several minutes in length will help people form a more accurate mental model of the robot’s social abilities. Consequently, uncanny feelings should decrease over the course of an interaction once people’s expectations about a robot’s behavior align more with its true abilities.

Hypothesis 2 (H2):
Initial uncanny feelings towards a robot decline when people are given access to more proximal cues via an interactive encounter with it.

From social psychology we know that getting acquainted with somebody does not necessarily increase our liking of them [39]. An important factor for reaching a closer interpersonal relationship is similarity, a phenomenon known as Homophily. Apart from factors like race, ethnicity, age, religion, education, occupation, and gender, similar behavior and attitude is also favored in others [85]. If uncanny feelings decline in an interaction, how quickly this happens
might thus not just depend on the length and richness of the interaction but also on the personality of the robot. People could potentially prefer robots with personality characteristics close to their own or similar to their preference in other humans [85]. The body of knowledge in social robotics generally confirms this assumption and most studies found a preference for a match in personality with a robot [94, 130]. Joosse et al. made a more nuanced observation, suggesting that preference for matching or complimentary personality traits depend on the robot’s task [59]. However, much of the related work on robot personality was performed by manipulating the robot’s level of extroversion and the preference for matching or complimentary personality in other traits is still an open question.

Instead of a match in personality, it could also be a positive attitude in a robot that generally allows people to become familiar with it faster, as suggested in related work by Złotowski et al. [153]. Hwang et al. found that a robot’s level of extroversion, emotional stability, openness to experience, agreeableness, and conscientiousness were negatively correlated with the feeling of concern. Furthermore, the more extroverted a robot was perceived to be, the more enjoyable it was found, the more emotionally stable and conscientious it was perceived, and the more favorable it was rated [57]. This finding generally aligns with the results presented by Broadbent et al., who found perceived eeriness of a robot to be correlated with a less sociable, amiable, and trustworthy personality [19]. Even though the related work on the impact of robot personality on uncanny feelings is not conclusive yet, it suggests an increase in difficulty for a robot to overcome an initial uncanny perception if it displays personality traits seen as less favorable.

**Hypothesis 3 (H3):**

If interactions can cause a decrease in uncanny feelings, less favorable personality traits in a robot can slow down this process.

Zibrek et al. found that personality-driven behavior, which was in stark contrast to what would have been expected from a certain appearance type, increased eerie feelings towards a virtual character [152]. Hence, it is possible that the perception of what qualifies as less favorable personality traits in a robot depends not just on the personality of the human interaction partner or the robot’s task but also on its appearance. Moreover, people were found to ascribe more positive personality traits to more human-like as compared to mechanical robots [19, 25]. The embodiment of a robot and specifically its perceived human-likeness is thus an important factor to be considered when studying the impact of its personality on uncanny feelings towards it.
3.3 Repeated Exposure and Interaction (H4, H5)

In order to examine the implications of uncanny feelings on human-robot interaction, it is crucial to understand whether these feelings are persistent over repeated exposures. A well-known effect in social psychology, the mere exposure effect, suggests that first impressions may be altered over time [149]. It posits that repeated exposure to a stimulus increases people’s affective rating of it, which was in contrast to other established theories like the novelty effect at the time it was first introduced. The novelty effect states that people “will turn toward a novel stimulus in preference to a familiar one” [149]. Zajonc suggested, however, that the preference towards a novel stimulus may be representative of a curiosity towards it rather than a positive affect [149]. While empirical evidence was sparse initially, Bornstein found overwhelming empirical support for an exposure-affect correlation in his meta-review in 1989 [17]. The most common explanation he found was two-folded: Habituation or a feeling of familiarity reduces threat, which may lead to a more positive rating compared to the insecurity that comes with an unknown stimulus. The rating plateaus or even decreases after a certain number of exposures, which might be explained by an increased level of boredom. Dijksterhuis and Smith proposed that it could also be affective habituation that leads people to rate both negative and positive stimuli they have encountered more often as less extreme [34]. Bornstein found substantial evidence that the exposure-affect relationship is stronger for more complex stimuli, which later led to linking the mere exposure effect to perceptual fluency. Independent of the exposure-affect relationship, researchers found perceptual fluency to generally increase liking of a stimulus [144]. This could explain the mere exposure effect in two different ways: Repeated exposure could lead to a higher perceptual fluency and the sense of familiarity derived from it could in turn lead to an increased affect. Whether familiarity is indeed linked to a positive affect is, however, still debated. Moreland and Beach, for example, found repeated exposure to have a strong effect on the ratings of attraction and similarity, but only a weak one on the sense of familiarity [89]. Another explanation could be that the reward given by the brain for making progress on processing a complex stimulus could be confused with a liking for the stimulus itself [37].

Since robots are a fairly complex stimulus and complex stimuli have been shown to increase the exposure-affect relationship, it can thus be hypothesized that the same effect translates to robots with an eerie first impression. If this hypothesis can be confirmed, it would be a further indicator that uncanny first impressions have a low impact on people’s future relationship with a robot. Although some research suggests that repeated exposure to negative stimuli can increase negative feelings, this presumes people already being familiar with and having a firm negative opinion about the stimulus [45]. As discussed earlier, people’s exposure to human-like robots is sparse, limiting the potential for negative preconceptions about them. This leads us to hypothesize that
a positive exposure-affect relationship could be observed even for robots initially perceived as uncanny. To our knowledge, only a master’s thesis at the Arizona State University explicitly investigated the effect of repeated exposure on people’s eerie feelings towards artificial agents and two android robots [28]. In his thesis, Corral did not find a significant effect of exposure on the perception of eeriness. However, it is unclear whether the images of the android robots used in his thesis were identifiable as such. With a maximum of three exposures, his study was also rather short in comparison to the related work on the mere exposure effect. We thus hypothesize that a more frequent exposure to a previously unknown robot can still decrease people’s uncanny feelings towards it.

**Hypothesis 4 (H4):**
Uncanny feelings towards a robot decreases merely by being repeatedly exposed to it.

Not just repeated exposure but also repeated interactions between two humans usually have a positive effect on their reciprocal attitude towards each other [39]. Repeatedly meeting and conversing with someone gives people more possibility to gain favorable impressions, reduce uncertainty, and increase perceptual fluency [104], which is generally linked to an increase in affect [103]. If the other becomes unappealing or causes boredom, the context becomes competitive or interpersonal conflicts arise, repeated interactions can also negatively influence the relationship between the two [39]. Reduced uncertainty and increased perceptual fluency should generally decrease uncanny feelings towards a robot both when taking the perceptual mismatch and the categorization ambiguity theory into account. While factors like boredom could potentially decrease people’s overall rating of the robot over time [68], this should influence other perceptual dimensions than the ones related to uncanny feelings.

**Hypothesis 5 (H5):**
Uncanny feelings towards a robot further decline over the course of repeated interactions.

While the body of knowledge on perception of robots in repeated interactions is generally sparse, the few studies that exist suggest that interacting with a robot more frequently indeed leads to a more positive affect. De Graaf et al. found people’s evaluation of a robot to be more favorable after six months of using it in their homes than after initially meeting the robot [30]. They partially explained their finding using the mere exposure effect. In their study,
however, people frequently interacted with the robot in their homes, which increases the relevancy of their results for understanding the impact of repeated interactions but heavily confounds the effect that the mere exposure had on the rating of the robot. Kim et al. exposed people to a NAO robot three times with a week of zero exposure in between and investigated their rating of the robot over time [61]. They found that familiarity had a positive effect on the social interaction with the robot (measured by their general attitude towards and attractiveness of the robot, among others) but not on engagement or enjoyment. Even though the scenario was not interactive in their study, the robot gave a short presentation in each of the meetings, which may have influenced people’s rating of the robot. In addition, none of the studies included a particularly uncanny robot, which limits conclusions we can draw about the persistence of the uncanny valley effect. Złotowski et al. were the first to measure the development of uncanny feelings towards a robot initially perceived as eerie over the course of three consecutive interactive sessions [153]. They found the level of uncanniness to decrease over the course of the three-part interaction session with a robot that lasted an hour in total. Even though their experimental design does not cover separate interactions with multiple days of zero exposure in between, their results suggest that repeated interactions with a robot indeed decrease people’s uncanny perception of it.
4. Methodology of the Empirical Investigations

In order to gather empirical evidence to better understand the durability of uncanny feelings towards robots and to support the hypotheses stated in Chapter 3, three prerequisites have to be considered. First, a robot platform is needed that can be perceived as both likable and uncanny with as little alteration as possible. Blended embodiments with a physical body and a virtual face texture were identified as a potentially suitable platform for the research conducted as part of this thesis. They are, however, a relatively new technology, which makes perceptual research involving these platforms sparse. Section 4.1 introduces the blended robot head Furhat V1 and discusses findings from a number of experiments, concluding that such a platform is indeed suitable for research related to the uncanny valley.

Second, scenarios need to be developed that allow the study of both people’s first impressions of robots as well as the development of their perception over a longer period of time. Several such scenarios were designed as part of this thesis. They can be categorized into still impressions comparable to seeing images of robots, non-interactive impressions comparable to watching video clips of robots, and live face-to-face interactive scenarios. An overview of these scenarios is given in Section 4.2.

Last, appropriate instruments need to be defined to measure people’s perception of robots and especially people’s uncanny feelings towards them. This thesis relies mostly on questionnaires but also explores non-verbal behavior to assess people’s level of uncanny feelings towards a robot. Section 4.3 takes a closer look at these measures and their implications.

4.1 Blended Embodiments to Study the Uncanny

In the related work, two main categories of robots were identified to elicit negative feelings: large and bulky mechanical robots and androids (cf. Section 2.2.1). People’s discomfort towards the first type of robots could potentially arise from a feeling connected to the fear of physical harm more than from an uncanny sensation. Consequently, many researchers have settled for human-like robots, such as androids, to study the uncanny valley. While this is in line with the type of robot originally envisioned by Masahiro Mori, android robots are rare and expensive and thus not available to most research groups.
The unavailability of androids is likely an important reason for the choice of an image or video presentation over the presentation of a co-present robot in many previous experiments.

For the purpose of this thesis, however, merely presenting people with images or videos of a robot is not sufficient. Hence, it was important to find a robotic platform apart from androids that (a) fulfills the requirement of being perceived as very human-like, (b) elicits uncanny feelings, and (c) is more easily available than a co-present android. Several promising approaches to eliciting uncanny feelings have already been suggested in related work on virtual agents. Broadbent et al. found that they could similarly manipulate people’s eerie feeling towards a Peoplebot robot, a physical robot platform with a two-dimensional screen as a head, by displaying different versions of a human-like face on its screen [19]. Based on this promising finding, the decision was taken to further study the suitability of blended embodiments for uncanny valley related research. A blended embodiment is a platform that combines physical and virtual features to enhance people’s interactive experience with it. For this thesis, the commercially available robot head Furhat was chosen [1]. Furhat is composed of a physical head on which a virtual face texture is projected from within. It thus combines the advantages of a physical robot embodiment, e.g. the possibility to accurately direct gaze in three-dimensional space [2], with the potential to easily alter the robot’s appearance. In addition, a blended embodiment allows an accurate modelling of its facial expressions, features otherwise only present in virtual humans.

The concept of projecting a virtual or real face onto a three-dimensional mask was first proposed two decades ago. In 2002, Yotsukura et al. developed a prototype in which a face was projected onto a mask worn by an actor [147]. In contrast to the back-projected approach, they used an external projector, which required a camera system for tracking the current position of the mask. Hashimoto and Morooka followed up with a proof of concept in which the projector was placed inside a half-sphere [47]. Delaunay et al. and Kuratate et al. refined this approach by building some facial features into the physical mask [31, 65]. Despite these promising prototypes, Furhat is the first back-projected robot head to become available commercially. In parallel to the Royal Institute of Technology, where the Furhat robot was initially developed, a team of researchers at the University of Denver designed and patented ExpressionBot [87], a robot head with similar design features to the Furhat robot. With Socibot1, a full-body robot which shares basic design characteristics with RoboThespian but is equipped with a fully back-projected head became available as well.

In the studies presented in this thesis, Furhat V1 was used. In comparison to the NextGen Furhat robot, the mechanical features of this robot are still visible: The mask of the robot is attached to a white box including the computer,

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1[https://www.engineeredarts.co.uk/socibot/](https://www.engineeredarts.co.uk/socibot/)
speaker, and control electronics. The projector and its related cables are visible in between the mask and the robot’s torso. Furhat V1 has only two degrees of freedom, allowing the robot to nod and shake but not to tilt its head. As previously noted, the appearance of the robot’s face can easily be altered by applying different virtual textures. Since back-projected heads are still a comparatively new technology and perceptual research with them is sparse, three different approaches were investigated to understand how to elicit uncanny feelings using such a blended embodiment.

4.1.1 Morbidity and the Uncanny

In his original paper, Mori suggested that an eerie feeling elicited by very human-like robots arises from an “instinct that protects us from proximal [...] danger [...] [which] include[s] corpses, members of different species and other entities we can closely approach” [90]. In their meta-analysis, Kätsyri et al. found some empirical support for this morbidity-hypothesis [60]. However, studies taking this hypothesis into consideration were overall sparse. The first approach to elicit uncanny feelings with a blended embodiment was thus based on Mori’s original idea of morbidity as a cause for the uncanny to extent the existing body of research on this hypothesis.

In order to create a version of the face that was perceived as morbid or unhealthy, the skin blood coloration of the face was altered, which was found to be a strong indicator of perceived health [120]. Following the approach by McDonnell et al., the skin texture of the human-like face was shifted to a more pale, yellow version and a red shimmer was created around the eyes [83]. The resulting texture is depicted in Figure 4.1 (second from right).

To test the hypothesis that a sick version of the face would be perceived as more uncanny than a healthy version of the same face, this texture was applied in the study presented in Paper V. The results obtained could, however, not confirm the hypothesis. On the contrary, we found the sick version of the

![Figure 4.1. Face textures from left to right: human-like, mechanical, sick alteration of the human-like face, morph V2 between the human-like and mechanical texture. All or subsets of these were used in experiments reported in Paper V, VI, and VII.](image)
face to elicit similar feelings in terms of warmth and discomfort as the healthy version of the face. The only significant difference was observed in the perceived social presence, which was found to be higher in the sick version than the healthy version of the face. Since the perceived health of the robot was not directly measured in the study, it is possible that people did not perceive the face as unhealthy but rather attributed the coloring of the face to technical limitations of the platform. This could have limited the sensation of morbidity and thus prevented the elicitation of uncanny feelings. More research is necessary to understand whether the non-significance of the results is due to the specific face texture chosen, the blended embodiment as a platform being unsuitable for this approach, or morbidity not being a cause of uncanny feelings altogether.

4.1.2 Gender and the Uncanny

One factor in the appearance that is easily adjustable in a blended platform is the robot’s gender. Tinwell et al. found people to have a higher level of uncanny feelings towards male virtual characters than female characters [134], especially when a lack of facial expressiveness in the upper part of the face conveys signs of psychopathy in the virtual human. They theorized that uncanny feelings may be related to people’s fear of psychopaths, which in turn is a phenomenon far more prevalent in males [134]. Green et al. made a similar observation, finding a decrease in the rating of creepiness in combination with an increase in rating the stimulus as female [44].

The study presented in Paper I was performed to understand if applying a male or female texture to the blended robot’s face can be used to manipulate people’s feeling of uncanniness towards the robot. The experiment involved three phases. In the first phase, people would see the robot showing an evenly colored face with barely visible lips and eyes. We consider this facial texture neutral since it does not include any facial details. In the second phase, participants were asked to rate their impression of the robot displaying the male or female face texture (cf. Figure 4.2). In the final phase, the robot either introduced itself using verbal and non-verbal interaction (multimodal condition) or

![Figure 4.2. The female and male face texture used in Paper I, both applied to an artificial agent and the Furhat V1 robot platform.](image)
displayed a series of facial expressions without using speech (unimodal condition).

Interestingly, the findings presented in Paper I contradict the results observed by Tinwell et al. [134]: *Participants in our study had a stronger initial uncanny reaction towards the female version of the robot than to the male version.* This first impression persisted when people were consecutively exposed to the unimodal behavior. However, the likability of the female robot exceeded the one of the male robot in case people were exposed to the multimodal behavior in the third step. Analyzing the perception of the neutral skin texture can provide an interesting context to this finding: The results indicate that the platform itself without a gendered texture applied is perceived as dominant and male. Adding a female texture to it thus creates an incongruence in people’s gender perception, while applying a male texture is congruent with the shape of the physical mask. This incongruence is resolved if the female voice is added, which decreases the uncertainty when it comes to the robot’s gender.

Overall, these findings suggest that *uncanny feelings can be elicited by an incongruence not only in the robot’s human-likeness but also in the robot’s gender.* This is in line with the suggestion by Bartneck et al., who proposed uncanny feelings to be multi-dimensional and not just dependent on an agent’s level of human-likeness [11]. It has, however, been shown, that people apply gender stereotypes to robots similar to other humans [36]. Thus, changing the robot’s gender has a variety of other implications, including the task its deemed suitable for. These confounding factors make the use of gender cues to elicit uncanny feelings be regarded with caution. The results do, however, show that a perceptual mismatch in the face could generally be a suitable approach to elicit uncanny feelings in a blended embodiment.

### 4.1.3 Anthropomorphic Incongruence and the Uncanny

In their review on explanatory theories behind the uncanny valley, Kätsyri et al. found most support for the hypothesis that “inconsistent artificial and human-like features” elicit uncanny feelings [60]. A widely used approach to create such incongruence in virtual agents is to create a morph between an artificial and human-like face. Following this approach, a morph V1 between a human-like face texture based on a photograph of a real human and a character-like texture was created. The latter had cartoon-like lips, eyes, and eyebrows and an otherwise plain skin color. The morph was created by blending between the two face textures\(^2\). The three resulting face textures are depicted in Figure 4.3.

The human-like and character-like texture as well as the morph V1 were used to investigate people’s ability to understand emotional facial stimuli performed by the agent as described in Paper IV as well as people’s spontaneous

\(^2\)PAINT.net photo editing package was used for designing morphs.
Figure 4.3. Face textures from left to right: character-like, morph V1, and human-like version. These textures were applied in the experiment reported in Paper IV.

and conscious mimicry of the robot. While 20 crowd-workers recruited on Amazon Mechanical Turk rated the morph V1 texture to be in between the human-like and character-like texture in its perceived anthropomorphism, likability, and perceived threat, using the same face texture on the real robot in a lab-based study involving 48 participants led to less promising results. While the robot’s level of human-likeness was indeed rated as significantly higher for the human-like texture compared to the morph V1, the three face textures did not differ in their perceived threat or likability.

When projected onto the robot’s face, face textures become slightly blurry, making subtle differences in facial features hard to spot. Consequently, it could be hypothesized that the morphing might have been too subtle for people to notice the incongruence. The character-like face texture was thus exchanged with a mechanical texture, visibly composed of different facial parts held together by screws. A morph V2 was created between the human-like and mechanical version which had clearly visible inconsistent human-like and mechanical features in the face (cf. rightmost texture depicted in Figure 4.1). This face texture was first used in the study described in Paper V. Contrary to what we expected, it was rated as more human-like, competent, and socially present than the human-like version of the face. However, people also rated their own discomfort with it significantly higher than with both of the original textures. Hence, the morph V2 was used as an uncanny stimulus in the main experiments included in this thesis.

4.1.4 Conclusion

The results obtained using a blended embodiment suggest that such platforms are indeed suitable for conducting research on uncanny feelings towards robots. There are three major advantages of such an embodiment: (1) it is much cheaper and thus easier to access for a broader research community; (2) it limits the confounding factors in conventional uncanny valley related research by keeping the underlying hardware and robot appearance between conditions;
and (3) it allows to create a physically and virtually present version of an agent with the same appearance. However, using a blended embodiment can still raise a different set of challenges: The potential of creating a very human-like appearance similar to a Geminoid robot is not feasible due to the very clear mechanical torso of the robot. Even though projecting a face onto the robot has many advantages, such as easy alteration of facial features, it comes with the disadvantage of making it difficult to see details in the face textures. This may be one explanation for the limited success of using the morph V1 and the ill version. The texture that can be projected onto the face is also limited by the physical shape of the mask. Approaches like using disproportionate facial parts, as performed by MacDorman et al., was thus impossible [75].

Despite the limitations of the platform, the promising results when using both an incongruence in gender cues and in the robot’s level of human-likeness can contribute to our understanding of the theories behind the uncanny valley. As discussed in Chapter 2, both the categorization ambiguity theory and perceptual mismatch theory have gained substantial empirical evidence in the related work. Findings from Paper I on robot gender can support both theories: The uncanny feelings elicited by the female version of the robot could potentially be grounded in the perceptual mismatch between the facial shape and texture directly or in the resulting ambiguity of the gender of the robot. Results from using the morphing technique, however, support the perceptual mismatch theory more strongly than the categorization ambiguity theory. Since the robot torso is mechanical in appearance, participants are not in doubt about the nature of the stimulus being organic or artificial. This differentiates our results from the findings on morphing in virtual faces, where uncanny feelings are commonly explained by the incapability of participants to decide whether they are presented with a photograph of a real human or an artificially created face. When using a blended embodiment, this categorization ambiguity disappears. What remains is the perceptual mismatch between the human-like and mechanical features in the face. Following this logic, one could assume that a very human-like texture in itself should elicit similar uncanny feelings, since it is in mismatch to the mechanical features of the robot torso. Our findings, however, do not support this hypothesis. Indeed, some participants find the robot embodiment uncanny with a very human-like face texture applied, often referring to the fact that a talking head on a table is a common theme in horror movies. Despite this association, however, it seems that participants are generally focused on the face when interacting with the Furhat robot and pay little attention to its torso. The fact that the torso does not serve any interactive purpose might consequently make the perceptual mismatch between the face and the torso less dominant. It would be interesting to use a full-body robot like the Socibot in future experiments and understand whether a mechanical body with a greater level of functionality creates a stronger perceptual mismatch with a very human-like face or whether it still requires a mismatch in the facial features to elicit uncanny feelings.
4.2 Scenarios

In previous work, most experiments investigating people’s uncanny feelings towards robots were based on still images or short video clips of a robot’s behavior (cf. Chapter 2). In the following, we call the first type of scenarios *still impressions* and the second *non-interactive impressions*. The aim of this thesis is to understand the role that interacting with a robot as well as novelty plays when forming our impression of a robot. Consequently, different types of scenarios are required, allowing an analysis of how people’s relationships with robots develop over the course of multiple interactive sessions. We call scenarios that fall into this category *interaction-based impressions*. In the following, we will discuss the scenarios included in this thesis, categorized by their level of exposure.

4.2.1 Still Impressions

As discussed in Chapter 2, many empirical studies investigating the perception of robots were carried out using still images of robots as stimuli. In such scenarios, participants were presented with the image of a robot for a fixed or flexible amount of time. They were then asked to rate the image on several scales, either while still having access to the stimulus or based on their memory alone. Experiments that fall into this category were often carried out online, thus making differences in color and brightness of different screen types a likely confounding factor. Studies of these kind play a minor role in the empirical investigations presented in this thesis. While Paper I and IV utilize a similar methodology, it was merely applied in pilot studies informing parts of the main experimental design, which was then conducted with a physically present robot.

Since the aim of this thesis is to investigate whether first impressions persist in (long-term) interactions, we consider it crucial to measure first impressions of physically present robots by adopting a methodology as close as possible to the related work obtained on robot photographs. This was achieved by placing a robot in front of a plain background and asking people to rate the robot after looking at it for several seconds. The robot displayed a face texture during the observation phase while remaining still and silent. These scenarios have been used in Paper I, V and VI.

4.2.2 Non-Interactive Impressions

A second level of familiarization common in the literature is the presentation of short video clips. While these clips can show the robot’s multimodal capabilities, they do not allow for an interactive exploration of the robot. Again, we approximated the same type of scenario using a physically present robot. The first approach was the development of a two-minute long elevator pitch
for the robot to introduce itself and its abilities. The introduction was fully scripted in the IrisTK framework [117]. It involved the robot talking about itself and displaying facial expressions and head nods. However, the robot did not acknowledge the human’s presence in any way. This form of introduction was used in Paper I and V.

Paper IV takes a more task-based approach. Participants were asked to watch the facial expression of the Furhat robot and indicate which emotion was displayed and, in a second step, mimic the facial expressions performed by the robot. While this approach substantially differs from the elevator pitch, it shares a main characteristic: The robot is using a scripted behavior developed without the human in the loop, which makes both of them similar in nature to the video stimuli used in the related work.

4.2.3 Interaction-Based Impressions

In order to investigate the persistence of first impressions, it is essential to develop scenarios that give people access to the robot’s full behavioral stream by allowing them to get to know the robot in an interactive way. This thesis focuses on cooperative game scenarios between a human and a robot that are fun and remain engaging even over the course of repeated interaction sessions to investigate the persistence of first impressions.

The 20 Questions Game

In the 20 Questions Game, one player thinks of a character and the other player tries to guess the character by asking a series of Yes/No questions. This scenario was used in Paper II and V. In both papers, the robot asked the questions and attempted to guess the character the human partner had picked. In Paper II, the guessing capabilities of the robot were developed by co-authors of the paper and the selection of characters was limited to Disney characters. Participants were asked to play multiple rounds with the robot and, before and after each game, the robot engaged them in a brief social chat. The knowledge-base and guessing behavior of the agent used in Paper V was based on the Akinator API3. Akinator is trained on thousands of games played over the internet every day, which allowed the robot to guess characters from any domain.

Interactive Modalities

Even though the game relies on verbal communication, the phrases for the human player responding to the robot’s questions are limited and can only belong to one of the following five categories:

- Positive, certain response (e.g., yes, absolutely)
- Positive, uncertain response (e.g., probably, sounds right)
- Negative, certain response (e.g., no, definitely not)

3https://en.akinator.com/
• Negative, uncertain response (e.g., probably not, I don’t think so)
• They don’t know the answer

The limited number of possible responses lowers the burden on the speech recognition and language understanding significantly, which allowed the robot in both Paper II and V to play the game fully autonomously. Due to a large training corpus and knowledge database, the robot could easily exceed human performance in the game.

In addition to the conversational part of the interaction, the robot used facial expressions where appropriate in the game. The robot also sought eye contact with the human using a Kinect camera mounted atop its head, which served as another clue to communicate the robot’s awareness of the human game partner.

**Personality**

The interactive capabilities of the robot described in Paper II were enriched by designing two personalities for the robot. One was defined as *lighthearted and optimistic* and the other as *impatient and quick to overreact*. The robot expressed the personalities by using verbal responses written by crowd-authors specifically for the respective personality, a voice tone, and facial expressions matching the robot’s attitude. Crowd-authors are untrained workers hired via a crowd-sourcing platform like Amazon Mechanical Turk, who are paid per task they complete on the platform. To understand whether people’s perception of the robot’s personality matched its design, we conducted a between-subjects experiment with the robot’s personality as an independent variable.

The experiment took place at the Disney Research Lab in Pittsburgh and 23 colleagues unfamiliar with the research project were recruited as participants. They gave informed consent to participate in the experiment and received monetary compensation for their time. Over the course of four days, they played the 20 Questions Game with the robot at least once a day. On average, people met the robot 10.87 times throughout the study. Each of the interactions was short ($M = 2.86\text{ min}$) and consisted of a brief pre- and post-game social chat and the game interaction itself. After the last session, participants were asked to rate the robot and its personality.

While the robot’s perceived competence and human-likeness was comparable between the two personalities, *two of its personality traits were rated significantly different depending on the personality design participants were paired with*. The robot that was intended to be optimistic and lighthearted was rated as more agreeable and emotionally stable as compared to the robot designed to be impatient and quick to overreact. The latter was also generally rated as less pleasant. In addition to rating the robot on several scales, participants were also asked to describe the robot in three words. The analysis of these descriptions showed that the words chosen to describe the optimistic robot were more positive and had a higher valence than the words used for the impatient version. Interestingly, *the robot’s personality did not influence people’s enjoyment playing with or talking to the robot.*
RDG-Map: A Pedagogical Reference Resolution Game

The Rapid Dialogue Map Game (RDG-Map) is a cooperative, fast-paced game about finding countries on the world map, which is described in detail in Paper III. The human plays the role of the Director or Tutor in the game. The goal of the Director is to describe a target country to the robot playing the role of the Matcher or Learner so it can select the same country on the shared screen placed in between the two (cf. Figure 4.4). The robot is allowed to make up to two guesses per target country – in case the first guess is correct, the team scores two points, otherwise they score one (if the second guess is correct) or zero points. As a team, the human and robot try to score as many points as possible in the ten minutes of game interaction. The target countries are pre-selected and displayed to the Director on a private screen.

Interactive Modalities

Natural Language Understanding is comparably complex in this scenario, since there are no constraints on how the human Director may describe the target country to the robot. While we did collect a large corpus of game interactions (cf. Paper iii) to develop parts of a fully autonomous version of the robot playing the game, the results of that are beyond the scope of this thesis. The experiments conducted within this scenario were thus obtained by remote-controlling the robot to ensure that poor performance of the robot’s language understanding would not negatively confound our findings. As detailed in Paper III, the interface for the human controller was designed based on an initial human-human data collection with players recruited via Amazon Mechanical Turk. The first version of the human-agent game was then deployed over the web and tested with 50 human subjects. Results from this pilot run served both as a training session for the human controller and to refine the game dynamics and controller interface. In all experimental sessions, the same researcher following a strict protocol was responsible for controlling the agent.

Figure 4.4. Schematics of the experimental setup during the RDG-Map game as described in Paper III and VII, including the operator interface (top left), the Director screen on the iPad (bottom left) and the two RGB cameras’ angles of view (right). A comparable setup was also used in the experiment reported in Paper VI.
Paper VI and VII deployed the RDG-Map game as a scenario. Every interaction session for these two papers was about 14 minutes long and consisted of a 10-minute long game interaction and a pre- and post-game social chat of approximately two minutes each. The social chat was fully remote-controlled as well.

**Personality**

The study presented in Paper VI used a slightly refined version of the personalities developed for the 20 Question Game described above. In this study, one personality was described as *lighthearted, optimistic, and determined to engage and encourage others in every situation* and the other as *snarky, with little patience for life’s imperfections and people’s mistakes, and receiving pleasure from challenging others*. The conversational content was authored by crowd-authors on Amazon Mechanical Turk again. However, a refined methodology was used to give the authors a better understanding of the current mood of the robot when authoring an utterance for it. Instead of giving the crowd-authors the personality description of the robot directly, they were hence given a current affect (excited, impatient, or indifferent) with a modifier (slightly or extremely). This technique was developed to have a more natural progression of the robot’s affective state and is further described in Paper iv, which is beyond the scope of this thesis. In addition to the voice content, facial expressions were used to communicate the current affective state of the robot.

### 4.3 Measures

#### 4.3.1 Questionnaires

This subsection introduces the questionnaires used to measure people’s perception of a robot as well as the ones deployed to gather some information about the participants in the experiments reported in this thesis.

**Measuring the Perception of the Robot**

**Anthropomorphism**

Mori originally described the level of uncanny feelings towards a robot as a function of its perceived human-likeness. Hence, a measure of the robot’s anthropomorphism was included in all experiments conducted as part of this thesis. Two different scales were used to measure this concept. In the majority of papers, the respective scale from the Godspeed questionnaire was used [12]. The scale has a high internal consistency reliability: According to the paper it was originally introduced in, the reliability score ranges between $\alpha = .929$ and $\alpha = .856$, depending on the condition [12]. Ho and MacDorman reported a similar consistency of $\alpha = .91$ [51]. However, they also found the anthropomorphism to be highly correlated with the robot’s likability, thus failing to measure it independently of people’s affect towards it [22, 51]. While
a failure to decouple the different concepts is problematic, it remains the most widely adopted scale in the HRI literature and using it thus assures comparability to related work. In the more recent studies discussed in this thesis (Paper V, VI and VII), the scale of warmth from the Robotic Social Attributes Scale (RoSAS) was added [22]. This scale covers the factors feeling, happy, organic, compassionate, social, and emotional and thus deliberately combines the concept of human-likeness with positive traits. Its internal reliability is similar to the anthropomorphism scale from the Godspeed questionnaire (α = .91) [22].

Uncanniness
As discussed in Section 2.2.5, the exact translation and meaning of the term uncanny is still controversial. In this thesis, two different scales to capture the concept of uncanny feelings were selected. The first scale is based on the threat scale proposed by Rosenthal-von der Pütten and Krämer [107]. It covers the items threatening, eerie, uncanny, dominant, and harmless (α = .886) and is used in Papers IV, VI, and VII. Since the majority of participants in our studies were non-native English speakers, many struggled with responding to the questions due to the specific terminology used. Specifically, the term “uncanny” and how it differs from “eerie” was often unclear. Hence, in more recent studies, another scale from the RoSAS was included to cover the concept of discomfort (α = .82) [22]. The individual factors included are aggressive, awful, scary, awkward, dangerous, and strange. Paper I even included a question regarding people’s familiarity with the robot [83]. However, from the responses it seemed like people’s interpretation of this question was whether they had seen this specific robot (or robot type) before, which is why this question was excluded in later studies. Problems with using different conceptualizations in studies related to the uncanny and how the different factors used in this thesis relate to each other is further discussed in Chapter 6.

Likability
In Mori’s graph, positive affect towards robots is essential to capturing people’s feeling towards robots ranging between mechanical and overly human-like robots. To measure these feelings, the likability of the robot was included in addition to their perception of uncanniness as a separate scale. In the early studies included in this thesis (Paper I, II and V), the likability scale of the Godspeed questionnaire was used (internal consistency between α = .923 and α = .842 according to [11] and α = .92 according to [51]). For the studies reported in Papers IV, VI, and VII, the likability scale from Rosenthal-von der Pütten and Krämer covering the items pleasant, likable, attractive, familiar, natural, and intelligent was adopted [107]. It has a slightly weaker but still good internal consistency (α = .827). Instead of using antonyms to mark the scales, which sometimes appear to cover more than one related affect [22], the likability scale by Rosenthal-von der Pütten and Krämer measures agreement with a given description based on a five-point Likert scale.
**Social Presence**
Understanding the influence of a robot’s co-presence on people’s perception of a robot is essential to examine H1. Thus, a short version of the social presence questionnaire developed by Harms and Biocca was applied [46]. In total, eight questions from the sub-scales *Co-Presence* (2 items, $\alpha = .84$), *Attentional Allocation* (2 items, $\alpha = .81$), *Perceived Affective Understanding* (2 items, $\alpha = .86$), *Perceived Emotional Interdependence* (1 item, $\alpha = .85$), and *Perceived Behavioral Interdependence* (1 item, $\alpha = .82$) were included.

In Paper V, we adapted a different scale from Lee et al. to further understand how the perception of social presence develops over time [67].

**The Robot’s Personality**
In the two papers involving robot personality (Paper II and VI), people were asked to judge the robot’s personality by filling out a short version of the Big Five Personality questionnaire. In Paper II, the Ten-Item Personality Inventory (TIPI) [42] was used. The questionnaire used in Paper VI is based on the Big Five Inventory-10 (BFI-10) [101].

**Competence**
When manipulating the appearance or personality of the robot, one can easily influence perceptual dimensions in addition to the ones intended to be manipulated. One dimension we were particularly interested in keeping equal across conditions was the robot’s perceived competence. Since our main scenarios are based on cooperative games, we were worried that people’s likability of the agent could be influenced by a difference in competence between the versions. We thus included scales to measure the robot’s perceived competence: Paper II made use of the *perceived intelligence* scale from the Godspeed questionnaire ($\alpha = .87$ according to [51]). For Paper V, VI and VII, we switched to the *competence* scale from the RoSAS including the items knowledgeable, interactive, responsive, capable, competent, and reliable ($\alpha = .84$) [22].

**Observer’s personal traits**
In addition to the perception of the robot, we also captured information about our participants. Apart from a demographic questionnaire that included a question regarding people’s self-assessed familiarity with robots and science fiction, we captured participant’s personality in Papers IV, VI, and VII [101] and their level of *fantasy* ($\alpha = .78$ for male and $\alpha = .75$ for female participants), *perspective taking* (M: $\alpha = .75$, F: $\alpha = .78$), and *empathic concern* (M: $\alpha = .72$, F: $\alpha = .70$) based on the Interpersonal Reactivity Index (IRI) [29]. Before interacting with the robot in the experiments included in Paper VI and VII, we also asked participant’s about their negative attitude towards robots (NARS, internal consistency between $\alpha = .648$ and $\alpha = .782$ depending on the sub-scale) [92].
4.3.2 Behavioral Measures

There are several drawbacks of using questionnaires when measuring people’s uncanny feelings towards a robot. First, questionnaires cannot capture the development of feelings continuously over a period of time. While it is possible to ask people to repeatedly fill out a questionnaire about their perception of a robot, it interrupts their experience with the robot and becomes tedious after several repetitions. Second, when studying uncanny feelings in young children (as we did in Paper xi), questionnaires may not always be a suitable approach [145]. Apart from the inability to read and fill out a questionnaire on their own at a young age, they also lack the self-reflection to be able to report their feelings on such complex scales. Finally, even adults can struggle filling out questionnaires if the terminology used is uncommon in their everyday language. For example, the term uncanny may be known to many on a theoretical level. However, if they have never experienced a feeling they would themselves describe as uncanny, they may have a difficult time relating their current feelings to this specific term. While the experiments published in this thesis rely on questionnaires to assess people’s uncanny feelings towards the robot, some preliminary experiments have been conducted looking into perceptual cues and their relation to uncanny feelings.

Task Success

Since most of the experiments included in this thesis are task-based, measuring how well people perform in the task can give valuable insights into the consequences uncanny feelings can have on people’s behavior. In Paper IV, people were tasked with recognizing emotional facial expressions performed by the robot by selecting an emotion from a pre-defined list. Their success in picking the intended emotion as well as their self-reported confidence with the selection were recorded as their success in performing the given task.

In Paper II and V, participants played the 20 Questions game with a robot. Success in the game was measured by the number of correct character guesses made by the robot. Similarly, in the RDG-Map game used in Paper VI and VII the total points scored by the human-agent team within the ten minutes of game time were considered to measure participant’s success in the task.

Gaze and Pupil Dilation

Two measures that could potentially be meaningful for detecting people’s uncanny feelings toward robots can be extracted from tracking participant’s pupils during an interaction: First, related work suggests that their pupils dilate less when being confronted with an uncanny robot as compared to both more mechanical and more human-like ones [105]. Second, people’s discomfort with a stimulus could trigger gaze aversion, leading them to pay less attention to the robot stimulus compared to when interacting with a likable agent [125]. However, all experiments utilizing explicit tracking of people’s gaze
behavior or pupil dilation so far involved a very brief exposure of a few seconds to the stimuli under investigation. Ideally, such measures could also be applied in long-term interactions with robots to gather a continuous understanding of people’s feelings towards the robot. To examine the reliability of pupil tracking over extended periods of time, we asked participants to wear a Tobii eyetracker when playing the RDG-Map game with the robot as described in Paper VI and VII. Findings from the respective analyses are, however, not directly related to the hypotheses of this thesis and hence not discussed in further detail.

**Mimicry**

Mimicry describes the “imitation of an interaction partner’s posture, facial expression, or speech characteristics” [49]. People mimic others consciously or subconsciously for different reasons that mostly revolve around building or maintaining relations with others and recognizing emotions [48]. In their overview paper on emotional mimicry, Hess and Fischer reported that people show less subconscious mimicry when their attitude towards the interaction partner is negative or when they perceive the other as an out-group member [48]. Thus, the presence or absence of spontaneous mimicry of an agent’s emotional expressions could give us an indication of people’s general attitude towards a robot. Only Hofree et al. have specifically investigated mimicry of an uncanny artificial agent [55]. They found that people spontaneously mimicked a co-present robot despite rating it as uncanny. However, they only compared the mimicry to a human and not to other, less uncanny artificial agents. Hence, their study does not allow us to draw conclusions regarding whether people show less spontaneous mimicry the more negative their attitude towards an artificial agent is.

We designed an experiment to understand (a) whether people show less spontaneous facial mimicry when being asked to identify a robot’s emotional state from its facial expressions and (b) whether they mimic an agent less well when being instructed to do so when the robot to be mimicked is perceived as uncanny. Two independent variables were manipulated in the experiment: The agent’s embodiment (3D co-present, 3D video recorded, 2D co-present) was manipulated within-subjects, and the agent’s face texture (human-like, character-like, morph V1) between-subjects. The agent displayed the six basic emotions, happiness, anger, surprise, fear, sadness, and disgust [35]. A webcam was placed so it could capture a high-resolution frontal recording of people’s face when watching and imitating the robot. Using computer-vision-based measures, we first detected people’s activation of their facial action units. When examining instructed mimicry, we expect people to be able to follow the dynamics of the facial expression displayed by the agent as closely as possible. Thus, we used Cross-Recurrence Quantification Analysis (CRQA) to calculate the dynamic overlap between the movement of the participant’s and the agent’s facial action units (cf. Paper v). For spontaneous mimicry,
however, one does not expect people to follow the same dynamics displayed by the agent. Instead, any activation of congruent facial action units of more than three consecutive frames was considered mimicry (cf. Paper i).

We found that the embodiment of the agent had a significant influence both on people’s spontaneous as well as on their instructed facial mimicry. The level of human-likeness manipulated by using different face textures, however, had no effect. In other words, people’s ratio of spontaneous mimicry and their success in the instructed mimicry task was not lower when the agent displaying the facial expressions was considered uncanny. However, one important factor that might have influenced our findings is the specific setup of the experiment. Instead of interacting with the agent, people were merely exposed to pre-recorded behavior. The setting in which people met the agent was thus task-based and not social. Consequently, people used spontaneous facial mimicry to subconsciously help them understand the emotional state being communicated by the agent, not as a means to bond with the agent. Based on this specific experiment, we are hence unable to conclude whether the presence or absence of facial mimicry is an indicator of their uncanny feelings towards an agent. In order to further examine this hypothesis, spontaneous mimicry of several agents with varying levels of human-likeness would need to be examined in a social setting, like the pre- and post-game conversation in Paper VI and VII.
5. Results

In Chapter 2, several gaps in the existing body of work were identified, which limit the potential to draw conclusions about the effect of uncanny feelings on human-robot interaction. This chapter summarizes findings from several empirical investigations that have been conducted to address these gaps. One methodological inconsistency that was found in the related work was in relation to the physical co-presence of an agent. Section 5.1 reports findings from an experiment that was specifically conducted to investigate the influence of an agent’s co-presence on people’s uncanny feelings towards it (H1). The two experiments presented in Section 5.2 then investigate the effect of interactions on uncanny feelings towards a robot (H2). Since Zlotowski et al. have identified the robot’s attitude to be a major influencing factor on people’s feelings towards an uncanny robot [153], experiments further investigating this effect are presented in Section 5.3 (H3). In Section 5.4 and 5.5, we then focus on the long-term effect of the uncanny valley and report findings from two experiments in which participants were repeatedly exposed to a variety of robots (H4), or had several interactions with an uncanny robot (H5).

5.1 Physical Presence (H1)

In Section 2.2.2, it was shown that most of the experiments investigating uncanny feelings used images or short video clips instead of a co-present robot. Human-robot interaction, on the contrary, is traditionally defined as involving physically present robots [41]. Hence, it is important to understand whether findings from images and video clips of robots transfer to people’s feelings towards robots physically co-present with them. According to Mori’s original hypothesis, eerie feelings are a self-preservation reflex of the human brain to protect us from proximal danger [90]. The sense of danger should be more prevalent in a co-present robot compared to one presented on a screen, which would suggest that co-present robots should be rated as more uncanny than their virtual counterpart. Consequently, H1 states that uncanny feelings towards a co-present robot should exceed those of a virtually present one.

The Effect of Co-Presence in Facial Expression Recognition (Paper IV)
The study presented in Paper IV directly compared three types of artificial agents with regard to both people’s perception of and their ability to attribute emotional state to it. Each participant got to interact with a Furhat robot as
described in Section 4.1, a video recording of the robot, and a virtual agent with the same face texture applied (within-subjects). As a baseline, a video recording of a human was included as a fourth stimulus. Both the robot and the virtual agent preformed the facial expressions live during the experiment and are thus considered co-present. The order in which the different versions of embodiment were shown to participants was shuffled. In addition to the agent’s embodiment, the robot’s face texture (human-like, character-like and the morph V1) was manipulated between subjects to explicitly compare agents eliciting uncanny feelings to more likable versions of the agent. The robot and the virtual agent both displayed the six basic emotions, as defined by Ekman and Rosenberg [35], and participants were asked to select which of the emotions was shown by the agent.

The experiment started by taking informed consent from participants and asking them to provide demographic information. Participants were seated at a table so that the agent would roughly be at their eye level. They were told their task was to identify which expression each of the agents was displaying and to indicate how certain they were of their response. The three agents and the human displayed each of the six basic emotions twice, leading to a series of 12 expressions per embodiment. The questionnaire system was coupled with the robot controller, so that the robot would only display the next expression once the participant finished responding to the questions. The order of the facial expressions was quasi-randomized with the exception that no expression occurred twice in a row. After the participants had rated all 12 emotions for one of the agents or the human, they answered a series of questions about their perception of that particular embodiment before continuing with the next one.

We found that the two co-present agents, the robot and the virtual agent, were perceived as overall more threatening than the two video recordings. The difference between the virtual agent, the embodiment rated as most uncanny in our experiment, and the video recording of both the human and the robot reached significance. The level of threat elicited by the co-present robot was only significant in comparison to the video recording of the human. The human recording was not only considered the least threatening, it also received the highest rating of likability, which was significant compared to the virtual agent and the video recording of the robot. Interestingly, the co-present robot received the second highest rating of likability, which was significantly higher than the one given to the virtual agent. An interaction effect with the agent’s level of human-likeness could not be observed both for the perceived likability and threat, suggesting that this effect is present independent of the face texture applied.

We had hypothesized that the difference in the perception of uncanniness could be correlated with the agent’s perceived social presence. While we found an effect of the agent’s level of human-likeness on the perceived social presence, the embodiment only had a marginal effect on it. The video-recording of the human was generally perceived as the most socially present,
especially in the dimension of affective understanding. The ability to attribute emotional state did not vary between the three different embodiment versions. Similarly, the difference between the three artificial embodiments was not significant in any of the other dimensions we investigated. A correlation analysis confirmed this finding and revealed no interdependence between the ratings of social presence and perceived threat.

5.2 Interactive Scenarios (H2)

In social psychology, first impressions are commonly defined as short encounters with a previously unfamiliar person of less than five minutes in length [4]. In these encounters, people usually get access to the full behavioral stream. When studying uncanny feelings towards robots, on the contrary, participants were generally exposed to a robot for less than 12 seconds, which is significantly shorter than in the common definition of first impressions. In addition, their encounter with the stimulus was often limited to the visual observation of the robot, occasionally accompanied by an audio stream. As stated in H2, we believe giving people access to a more complete set of proximal cues of a robot allows them to form a more accurate mental model of it, which in turn leads to more familiarity and less uncanny feelings.

The 20 Questions Game (Paper V)

The study presented in Paper V was designed to understand the effect of multimodal interactions with a robot on people’s perception of it. The 48 students participating in this experiment were exposed to the Furhat robot, a platform they had never interacted with before. It was introduced to the participants in three stages (cf. Section 4.2): They first saw a still version of the robot, the robot then introduced itself, and they finally played the 20 Questions Game with it. While each participant was exposed to all three stages (within-subjects), the face texture applied was manipulated between participants.

The experiment was carried out in the Social Robotics Lab at Uppsala University. After giving informed consent and filling out a short demographic questionnaire, participants were exposed to the robot for the first time. They were asked to look at the robot for a few seconds and then report their first impression on an iPad placed in front of them. The exact time of exposure was not controlled. Their perception was measured on the scales of anthropomorphism, social presence, and social attitude. The questionnaire was followed by the robot introducing itself using a two-minute long prerecorded elevator pitch. Participants rated the robot on the same scales as after the first stage, before the robot continued with the 20 Questions Game, as detailed in Section 4.2. The experiment was concluded by measuring people’s perception of the robot once again and asking them about their experience in a semi-structured interview.
Figure 5.1. The development of people’s perception of the robot’s perceived anthropomorphism, warmth, competence and discomfort throughout the interaction. Significant differences are indicated by * ($p < 0.05$), ** ($p < 0.005$), and *** ($p < 0.001$). Anthropomorphism was rated on a five-point Likert scale, warmth, competence, and discomfort on a seven-point scale.

Data gathered using this setup suggest that the first impression of the robot was positively adapted over time (cf. Figure 5.1). Depending on the specific perceptual dimension, it either significantly changed after the robot introduced itself or after playing the game with the robot. This effect was observable for all the perceptual dimensions covered in the experiment: The robot’s human-likeness and competence was judged as significantly higher after playing the game with it, while its social presence and warmth was already rated higher after the robot introduced itself. The discomfort with the robot similarly decreased after the robot’s short introduction. These results are a first indicator that people’s initial impression of a robot is not persistent. The analysis of the interview responses revealed that people seemed to have had a difficult time reflecting about the robot in the first stage, because “it feels like [the robot] is just there.” Another participant reported: “[When] you haven’t talked to it, then it’s just dead. It’s just nothing. It’s kind of not even a robot before it moved.”

The RDG-Map Game (Paper VI)
The interactive capabilities of the robot in the 20 Questions Game were limited and many participants mentioned the lack of possibilities to ask the agent questions and talk back and forth more freely as a shortcoming of the experiment. It is thus interesting to investigate whether the effects discussed in Paper
V could be increased by designing a more social and engaging interaction with the agent. The experiment presented in Paper VI was similar in structure to the study discussed in the previous section and followed a 3 x 3 x 2 mixed experimental design. Participants were once again introduced to the robot in three different stages. While the first impression was identical to the one presented in Paper V, the second and third stage were slightly adapted. The second stage became more interactive and already allowed for a brief multimodal interaction with the agent, thus representing a true, but short, thin slice experience. In the third stage, participants were asked to play the RDG-Map game with the robot (cf. Section 4.2). The appearance of the robot was manipulated between participants using the human-like, mechanical and morph V2 texture. As a novel factor in comparison to the previous study, we introduced personality to the robot’s responses and behavior, which was again manipulated between subjects. Results regarding the influence of the robot’s personality will be discussed in greater detail in Section 5.3.

The experiment was conducted at the Tekniska Musset (Technology Museum) Stockholm. Participants were mostly recruited in the entrance of the museum and asked to provide informed consent and fill out a short demographic questionnaire outside the experiment room. They were then invited to enter the experiment space in which they were equipped with a Sennheiser close-range Microphone and Tobii eye-tracking glasses. The robot, still hidden under a blanket during the setup phase, was uncovered as soon as the recordings started. Participants were asked to fill out a questionnaire about their first impression of the robot after looking at it for a few seconds. The robot then initiated a short social chat to introduce itself and get to know the participant as soon as the first questionnaire was finished. Participants subsequently filled out the same questionnaire about their perception of the robot before playing the RDG-Map game with it. The game was followed by a post-game social chat. Once the interaction was over, participants were prompted to fill out the perceptual questionnaire about the robot for a third time. Before being debriefed outside the experiment space, they were given a final questionnaire about their overall experience with the robot and the game.

Like in Paper V, the perceived competence of the robot was significantly altered by playing the game with it. Participants rated the robot as being more competent after playing the game compared to both the first impression of the robot and their perception after the pre-game social chat. Furthermore, allowing people to interact with the robot significantly influenced the perceived likability and uncanniness of the robot. More specifically, the robot was liked significantly more and was judged as significantly less threatening after playing the game with it compared to the first, non-interactive impression.
5.3 Personality in Interactions (H3)

The evidence presented in the previous section could lead to the assumption that getting to know a robot generally alters people’s perception and leads to a more favorable impression of it. Findings reported by Złotowski et. al., however, suggest that the attitude of a robot influences whether people’s likability increases when interacting with an uncanny robot [153]. We thus hypothesized that the decrease of uncanny feelings towards a robot when being exposed to more proximal cues depends on the specific personality traits displayed by the robot (H3).

Story-Based Perception of Robot Personality (Online Pilot Study)

In this pilot experiment, participants were introduced to a robot through a short story accompanied by an image. The independent variables were the robot embodiment and the robot personality. Both independent variables were altered between participants. The robot embodiment included three images of the Furhat robot with different face textures applied (human-like, mechanical, morph V2). The robot’s personality was either described as lighthearted, optimistic, and determined to engage and encourage others in every situation (optimistic personality); snarky, with little patience for life’s imperfections and people’s mistakes, and receiving pleasure from challenging others (impatient personality); or it was not mentioned (control condition).

210 participants were recruited on Amazon Mechanical Turk to participate in the data collection. They were first asked to read a short story about the robot Neil who is playing a game about finding countries on a world map with a human game partner. The narrative was inspired by the RDG-Map scenario and ended with a description of the robot’s personality and how it informs the robot’s responses to participants in the game. This sentence was removed entirely in the control condition. Reading the story was not timed and participants could continue to the next page at their own pace. They were then asked to fill out a questionnaire about the robot’s personality and their perception of the robot on the dimensions anthropomorphism, likability, perceived threat, and discomfort. Two of the questions included were attention checks designed to filter out participants who did not read the story with sufficient thoroughness.

70 participants were excluded from the data analysis because they did not pass the attention checks. The remaining 150 participants (Male: 79, Female: 60, Other: 1; Age: $M = 36.34$, $SD = 11.93$) were evenly distributed between the 9 conditions, such that five conditions had 15 and four had 16 crowd-workers assigned. Most of the participants had attended university before, with 57.33% ($N = 86$) holding a bachelor’s and 14.67% ($N = 22$) a master’s degree. 42.67% ($N = 64$) reported they are currently or had previously studied Computer Science or a related subject.
Figure 5.2. People’s perception of the robot’s personality for the robot being described as optimistic, impatient, and for the robot without explicit personality description (control). Significant difference are indicated as * for \((p < 0.05)\) and *** for \((p < 0.001)\).
Figure 5.3. People’s perception of the robot’s anthropomorphism, threat and likability on a five-point Likert scale (left) and discomfort on a seven-point Likert scale (right) for the robot being described as optimistic, impatient, and for the robot without explicit personality description (control). • denotes a trend of \( p < 0.1 \), * indicates a significance of \( p < 0.05 \).

A personality description was not significant, \( p = .98 \). Furthermore, the optimistic robot was perceived as the most conscientious \( (M = 4.0, SD = 0.12) \) compared to the impatient robot \( (M = 3.87, SD = 0.12) \) and the control condition \( (M = 3.59, SD = 0.13) \). However, only the difference to the control condition was significant, \( p = .049 \). These findings are interesting, because they seem to suggest that people’s implicit assumption of how a robot behaves coincide with the impatient and provocative personality, not with the optimistic one. A visualization of the perceived traits for the three personality conditions is depicted in Figure 5.2.

In line with the perceived personality of the robot, the optimistic version was also judged to be the least threatening \( (M = 2.35, SD = 0.1) \) compared to the impatient robot \( (M = 2.82, SD = 0.11) \), \( p = 0.12 \), and the robot without an explicit personality description \( (M = 2.71, SD = 0.13) \), \( p = .069 \) (cf. Figure 5.3). This suggests that a robot with a positive and engaging personality could potentially help overcome the initial uncanny feelings caused by the robot. Only when it comes to likability, the description of the impatient robot personality had an influence on people’s perception of it. The impatient robot was perceived as the least likable \( (M = 2.94, SD = 0.13) \) in comparison to the optimistic robot \( (M = 3.38, SD = 0.12) \), \( p = .054 \), and the control condition \( (M = 2.26, SD = 0.14) \), \( p = 0.22 \).
Personality Perception in the RDG-Map Game (Paper VI)

The online pilot contributed evidence showing that explicitly providing people with a description of a robot’s personality influences how uncanny they perceive it as. In Section 4.2, it was discussed that such distinguishable personalities can be conveyed in multimodal interactions with a robot. This section hence investigates whether a robot’s personality traits alter people’s level of uncanny feelings towards it within an interactive scenario. The findings are presented in Paper VI and follow the experimental design as described in Section 5.2 for the RDG-Map game.

The expression of the robot’s personality was designed following a similar procedure to the one discussed in Paper II. The robot’s utterances were crowd-authored for a given personality. However, in order to ensure a higher consistency between the strength of the expressed affect in these utterances, the crowd-authors were provided with the current affective state of the robot in addition to its general personality. This approach is further discussed in Paper IV, which is not included in this thesis. The verbally expressed personality was supported with affective facial expressions. As dependent variables, not only did people rate the robot’s personality, they also indicated how uncanny they perceived the robot during the interaction. Analysis of results obtained in this study thus allow us to link the expressed personality of the robot to people’s uncanny feelings towards it and to investigate how these feelings develop over the course of the interaction.

![Box plot](image.png)

*Figure 5.4. People’s rating of the robot’s perceived anthropomorphism, threat and likability on a five-point Likert scale (left) and discomfort on a seven-point Likert scale (right) for the impatient and optimistic personality. * indicates a significance between conditions of \((p < .05)\).
The two personalities of the robot were distinct in their perception. In line with the findings from Paper II and the online pilot study, the impatient robot was rated as significantly less agreeable and more neurotic than the optimistic one. Furthermore, the optimistic robot was perceived as more conscientious than the impatient robot. This was likely influenced by the interpretations of the crowd-authors when receiving the description of the robot. The impatient robot often said lines like “I don’t really care if it is wrong or not anyway,” thus giving the impression it was less invested in the outcome of the game.

The personality of the robot did alter how people perceived it in only one of the dimensions we investigated (cf. Figure 5.4): The impatient robot was overall perceived as more threatening than the optimistic robot, while the perceived likability did not differ between the two conditions. We did not find an interaction effect between personality and interaction stage, which suggests that the personality of the robot did not influence how fast uncanny feelings towards the robot declined. When analyzing the difference between the two personalities at each stage of the interaction separately, however, it can be seen that the difference in perceived threat only becomes significant after participants finished playing the game with the robot. When examining Figure 5.5, it becomes apparent that people’s uncanny feelings towards the optimistic personality declined throughout the interaction, while the feeling of threat towards the impatient personality persisted. These findings suggest that the potential to overcome initial uncanny feelings may indeed depend on a robot’s behavior and that this effect intensifies the longer people are exposed to it.

![Graph](image)

*Figure 5.5. Development of people's feeling of threat (left) and likability (right) towards the impatient and optimistic robot throughout the interaction.*
5.4 Repeated Exposure (H4)

The previous two sections discussed how an exposure to a more complete set of proximal cues can help lower the initial uncanny feelings towards a robot. Another phenomenon known to alter people’s first impression of a stimulus is the mere exposure effect. In 1968, Zajonc shared initial evidence showing that repeated exposure to a stimulus leads to a more positive attitude towards it [149]. The same exposure-affect relationship could be seen across a variety of stimuli, including nonsensical words and images of people [17]. We thus hypothesized that uncanny feelings towards a robot can be lowered by repeatedly exposing people to it (H4).

The Mere Exposure Effect and the Uncanny Valley (Online Study)

In order to provide empirical evidence for how the mere exposure effect relates to uncanny robots, we designed an experiment inspired by Perlman and Oskamp [96] and Bornstein and D’Agostino [18]. The experiment followed a 2 x 2 x 4 factorial design, with the independent variables (a) robot type (human-like or mechanical), (b) favorability of the robot (positive or negative first impression) and (c) the number of exposures to the stimulus (zero, one, five, ten). The images were selected based on an investigation conducted by Rosenthal-von der Pütten and Krämer [107]. They found the Geminoid HI-1 robot to be overall rated as very human-like, but also threatening. On the contrary, the Geminoid DK received a similar rating with regard to human-likeness, but peoples’ affective response was overall positive. Similar ratings were received for the two mechanical robots, with PR2 being rated as threatening, while Asimo was seen as likable.

The study was conducted online and 182 participants were recruited on Amazon Mechanical Turk. They received monetary compensation for their participation. The experiment started with participants giving informed consent about the study. Participants were told: “This is a study of how people perceive different types of robots. During the next few minutes, you will see a series of pictures. There will be about 2 seconds between pictures where you see a white image with a cross in the center. Between images, focus on the cross until the next image appears. Please pay close attention to the pictures you are seeing, as you will be asked a series of questions about some of them afterwards” (text adapted from [18]). This was followed by 34 images of robots, with each image being shown for two seconds with a two-second pause in between the images. Three of the target images were included in this screening: One was shown once, one five times, and one ten times. The other images were distractors showing other robots that were displayed once or twice each. In addition to the robot images, three pictures were included as attention checks to filter out participants that did not watch the image sets closely. The order of the images was quasi-randomized, with the constraint that the same image was not shown twice in a row. The experiment continued
with rating the four target robots on their human-likeness, likability, discomfort, and perceived threat one at a time. The robots were displayed in random order for the final ratings. In the end, participants were asked to provide some demographic information about themselves.

Based on the attention checks, 102 data samples were excluded from the analysis, leaving a final sample of ratings by 80 participants (age $M = 36.04$, $SD = 13.08$). About two third of participants were male ($N = 51$, 63.75%) and one third were female ($N = 28$, 35%). One participant did not identify as male or female. The majority of participants had a university degree (65% had a bachelor’s degree and 8.75% a master’s degree). 45% reported that they have or had previously studied Computer Science or a related subject.

A three-way ANOVA with robot type (human-like or mechanical), favourability of the robot (positive or negative first impression), and the number of exposures to the stimulus (zero, one, five, ten) was conducted on the four dependent variables, anthropomorphism, likability, discomfort, and perceived threat. All three independent variables had a significant influence on people’s rating of the robot’s anthropomorphism: As expected, the Geminoid robots were rated as significantly more human-like than the two mechanical robots, $F(1,312) = 140.39$, $p < .001$. Interestingly, the robots rated less favourable in the experiment by Rosenthal-von der Pütten and Krämer (the Geminoid DK and the PR2) were overall rated as more anthropomorphic, $F(1,312) = 7.8$, $p = .006$. The number of exposures had a significant influence on people’s perception of anthropomorphism as well, $F(1,312) = 6.25$, $p = .013$. The

Figure 5.6. The combined ratings for perceived likability (left), threat (center) and discomfort (right) rated after different numbers of previous exposure.
more often people had seen a robot before, the more human-like they rated it. A two-sided Spearman’s rank correlation analysis confirmed that the number of exposures was significantly positively correlated with the perceived anthropomorphism of the stimulus, $\rho = 0.13$, $p = .026$. As expected from the results by Rosenthal-von der Pütten and Krämer, the robots rated more favorable in their experiment also received a higher rating in likability in our experiment, $F(1,312) = 10.26$, $p = .002$. We did not find a significant influence of the robot type on people’s likability of it, $F(1,312) = 1.59$, $p = .209$. However, the more often people were exposed to the robot before, the higher they rated their likability of the robot, $F(1,312) = 9.29$, $p = .003$. A two-sided Spearman’s rank correlation analysis showed that there was indeed a significant positive correlation between the times of exposure and the likability of the agent, $\rho = 0.17$, $p = .003$.

Similar results were observed for the perceptual dimensions related to the agent’s level of threat: All three factors significantly influenced how threatening people evaluated the robot. The Geminoid robots were rated significantly more threatening than the mechanical robots, $F(1,312) = 33.43$, $p < .001$, and the agents classified as eliciting more negative feelings by Rosenthal-von der Pütten and Krämer were indeed rated as significantly more threatening, $F(1,312) = 4.51$, $p = .034$. For this perceptual dimension, the number of exposures to the robots had the opposite effect: The more people were exposed to the robots, the less threatening they rated them, $F(1,312) = 5.83$, $p = .016$. A two-sided Spearman’s rank correlation analysis confirmed the negative correlation between the number of exposures and the perceived threat of the stimulus, which almost reached significance, $\rho = -0.11$, $p = .056$. The rating of discomfort with the agent follows the same trend with the Geminoid robots being rated as eliciting significantly more discomfort, $F(1,312) = 10.25$, $p = .001$, and the Geminoid HI-1 and PR2 eliciting more discomfort than the Geminoid DK and Asimo, $F(1,312) = 5.99$, $p = .015$. The ANOVA only shows a trend in the influence of the number of exposure on people’s level of discomfort with the stimulus, $F(1,312) = 3.52$, $p = .061$. However, the two-sided Spearman’s rank correlation analysis revealed a significant negative correlation between the number of exposures and the level of discomfort elicited by the stimuli, $\rho = -0.12$, $p = .026$. Figure 5.6 depicts the ratings of the three perceptual measures related to the uncanny grouped by the number of previous exposures.

### 5.5 Repeated Interaction (H5)

The evidence discussed in this chapter so far suggests that first impressions of robots are not stable and can be altered either by interacting with or being exposed to them more frequently. This section puts findings into a long-term perspective by conducting an experiment studying people’s perception of a
robot in repeated interactions with multiple days of zero exposure in between.
Given the generally positive relation between long-term interactions and perception in social psychology and HRI, we hypothesized that uncanny feelings would further decline over multiple interactions with a robot (H5).

**Repeatedly Playing the RDG-Map Game with a Robot (Paper VII)**
The study presented in Paper VII followed a 3 x 3 mixed experimental design to investigate the effect of repeated interaction on people’s perception of a robot. Participants played the RDG-Map game with the robot displaying a human-like, mechanical, or morph V2 face texture (manipulated between subjects) two to three times with 3 - 10 days of zero exposure in between.

The first session started with participants giving informed consent, reading the game rules, and providing demographic information. They were then equipped with a Sennheiser close-range microphone and Tobii eye-tracking glasses. Once all recordings were started, the robot was disclosed to participants for the first time and – after the experimenter had left the experiment space – it initiated a short social chat. After the two-minute long chat, the robot asked the participant to fill out a brief questionnaire about their impression of it, before continuing with the geography game. The game was immediately followed by a post-game social chat. In the end, participants filled out another questionnaire covering both their impression of the robot and their engagement with the game.

In the beginning of the second and third session, the robot was covered by a blanket again. Before being uncovered, participants were asked to fill out a questionnaire about their perception of the robot to measure how accurately they remembered their previous impression of it. Once they completed the questionnaire, the recording was started, the robot uncovered and they had the pre-game chat, the game interaction and the post-game chat without a break in between. Both sessions concluded with the same questionnaire about their impression of the robot and the game.

The results obtained in this study indicate that different perceptual dimensions stabilize within different time frames (cf. Figure 5.7), suggesting that some traits can be judged accurately after a short period of time while others are heavily influenced by how familiar people get with the robot. People’s judgement of the robot’s human-likeness and competence, for example, remained unaffected by repeated interactions. While the human-likeness of the robot was significantly higher after playing the game with the robot for the first time, compared to after the pre-game social chat, the competence of the robot was not even affected by playing the game with it for the first time.

Traits related to the interpersonal relationship with the robot, e.g., likability and discomfort, were less stable. While the likability initially increased from the pre-game interaction to after playing the game for the first time and between the end of the first and second interaction session, it remained stable between the second and third session. The negative feelings seemed to dissi-
pate relatively slowly and over the entire duration of the experiment. People’s discomfort with the robot and its perceived threat initially decreased from the pre-game interaction to after playing the first game with it. The perceived threat then remained stable between the first and second session and only decreased after the second session again. The rating of discomfort, on the contrary, steadily decreased over all three sessions, causing only the difference between the first and third session to be significant.

Our experimental design further allowed us to study the effect of zero exposure on people’s memory of the robot. We found that people overall recalled their rating of the robot accurately on the dimensions included in our measures. A notable exception is the level of anthropomorphism, which was judged to be lower in the beginning of the second session compared to their rating in the end of the first session. Similarly, they recalled the robot as less anthropomorphic in the beginning of the third session than they perceived it in the end of the second one. In the beginning of the second session, people also recalled their discomfort with the robot as higher in comparison to their rating in the end of the previous session. In the third session, however, the recollection of their discomfort with the agent was accurate.

Figure 5.7. Observed time frame for perceptual dimensions to stabilize in our repeated interaction sessions. Arrows indicate increasing/decreasing trend.
6. Discussion

The aim of this thesis is to examine whether people’s first impression of uncanny robots as traditionally measured in the related work is characteristic of their future interactions with them. Three gaps in the related work on uncanny feelings towards robots were identified in Chapter 2 that limit our current understanding of the persistence of the uncanny valley:

1. While human-robot interaction scenarios rely on co-present robots, related work on the uncanny valley has mostly focused on images or videos to study the perception of robots.

2. Exposure to uncanny stimuli in the related work usually does not exceed a few seconds and is often limited to the appearance of the robot without giving access to the full behavioral stream. Uncanny feelings in interactive scenarios have rarely been studied.

3. Empirical investigations in the related work on robot perception almost unanimously limit exposure to a single session, neglecting evidence from social psychology showing that first impressions may be altered over time.

In combination, these design decisions entail that our knowledge on the uncanny valley is limited to first impressions of novel stimuli. Hence, while the related work on uncanny feelings gives an extensive insight into what in the appearance of an artificial agent or robot elicits an uncanny feeling at first sight, little is known about how these feelings develop once the novelty of the stimulus fades. This is, however, an important consideration, given that the related work often implicitly assumes enduring consequences of uncanny feelings, which will ultimately lead to the rejection of certain robots [153].

In the following, the results from a series of empirical investigations tailored specifically towards understanding the durability of uncanny first impressions in human-robot interaction scenarios as presented in the previous chapter will be discussed in relation to the hypotheses stated in Chapter 3 and findings from the related work summarized in Chapter 2. This chapter concludes by considering limitations of the studies presented and giving an outlook on follow-up research necessary to further deepen our understanding of uncanny feelings in human-robot interaction.
6.1 Findings

6.1.1 Co-Presence of a Stimulus (H1)

Based on the related work on physical presence as summarized by Li and Mori’s original hypothesis of uncanny feelings preventing the body from proximal danger [69, 90], we hypothesized that uncanny feelings towards a co-present robot would be stronger than towards a virtual representation of it (H1). Empirical evidence presented in Section 5.1 partially supports this hypothesis. Contrary to our expectations, the co-present Furhat robot was not the stimulus that elicited most uncanny feelings. Instead, uncanny feelings were strongest towards the co-present virtual agent, closely followed by the co-present robot. In our initial hypothesis, we assumed that the virtual agent, despite its co-presence, would elicit a similar level of uncanny feelings as the video recording of the robot, since both are represented virtually on a screen instead of physically present in the same room. Our results, however, show a difference in uncanny feelings elicited by the two co-present agents performing the facial expressions live during the experiment (the virtual agent and the physically present robot) and the two video recordings.

One possible explanation for our findings is that it’s not the physicality of the embodiment that elicits uncanny feelings but the presence of the agent. Based on the scale to measure social presence included in the experiment [46], we did not, however, find an influence of embodiment on the perceived co-presence of the agents or a significant correlation between the judgement of threat and the co-presence of the agents. It is possible that the chosen subscales (“I noticed the character” and “the character’s presence was obvious to me”) did not capture the concept of social presence that is important to distinguish the two representations. The virtual agent and the co-present robot both had the ability to act in the moment, while the video-recordings captured behavior of the past. According to Mori’s original theory, uncanny feelings originate from proximal danger [90]. A recording of past behavior poses less of an imminent threat than an agent capable of reacting in the moment. This is in line with work by Appel et al., who found a robot with agency to be perceived as more uncanny than an agent without [5]. It is possible that our virtual agent and co-present robot were judged as having greater agency in the moment, since they performed facial expressions live during the experiment. Even though the robot in the video recording theoretically possessed the same level of agency, it had no influence on the proceedings of the experiment. Thus, the perception of agency rather than the mere feeling of presence may be influencing people’s uncanny feelings towards an agent. The questionnaires included in this thesis do not provide further data to support this hypothesis. Future research should thus cover a broader range of questions to assess the difference in perception between video recordings and co-present agents in more detail.

78
As stated in Chapter 3, a confirmation of H1 would support the perceptual mismatch theory, since a physically present robot can be assumed to give access to more varied proximal cues than an image or video of it. More specifically, in our experiment we assumed that the physically present robot allows observing more proximal cues than both the virtual agent and the video-recording of the robot. Since we did not specifically measure the proximal cues observable by the human participants, we can not draw conclusions whether our failure to fully support H1 is due to a similar level of proximal cues observable in the two co-present agents (physically present robot and virtual agent) instead of the two virtual agents (video recorded robot and virtual agent), whether all platforms elicited the same level of perceptual mismatch or whether our results provide evidence against the perceptual mismatch theory. Given the difficulties in obtaining high-quality video recordings of the Furhat robot due to its back-projected mechanics, it is possible that facial features were indeed least observable in the video recording of the robot, which would limit the observable proximal cues in this version of the embodiment. Using a different robot platform allowing for more detailed video-recordings would be one further research strand to shed light on this question. Moreover, future work could gain additional insights by measuring the level of proximal cues observable in the different embodiment versions more explicitly.

The evidence that co-present agents elicit more uncanny feelings than video recordings of the same is important to consider since it suggests that the severity of uncanny feelings elicited by certain types of robots might have been underestimated if the measures were based on images or videos of the robots alone. Our results thus extend the work by Li [69], as they suggest that the physical presence of a robot does not only strengthen positive feelings, but amplifies negative perception as well. This is important for the human-robot interaction community, which relies on physically present robot platforms. For a better understanding on people’s definite uncanny feelings towards a platform they would meet in an interactive context, it is thus crucial to expand the number of studies on the uncanny valley involving co-present robots. While lab experiments with co-present robots are costly and time-consuming, two alternatives could be explored to study uncanny feelings towards co-present robots using remote participants: (1) Proof-of-concept implementations using co-present virtual agents for live interactions on the internet have already been developed over the past years. One such project is SimCoach, a virtual human helping veterans with symptoms of post-traumatic stress disorder [106]. The advantage of this approach is that it scales easily and allows multiple people to participate in an experiment simultaneously. However, more research is required to first ensure that uncanniness elicited by virtual agents is truly comparable to a robot platform matching in appearance as suggested by the findings in Section 5.1. (2) Using a live-stream of a robot that a participant can remotely interact with over the internet could be another alternative to pre-recorded videos [135]. While this setup increases the feeling of agency
the robot has during the experiment, it also limits the amount of people simultaneously participating and requires a much closer observation of the setup to ensure the robot operates correctly during the study. Again, more research is necessary to understand whether this remote setup can elicit similar feelings of uncanniness to a physically co-present robot. Eventually, it will be important to design experiments that involve physically co-present robots. The two proposals discussed above could, however, be a first step to link research on the uncanny valley with research on human-robot interaction more closely.

6.1.2 Interactivity in Human-Robot Encounters (H2, H3)

In the previous section, we discussed evidence suggesting that uncanny feelings towards co-present robots could be stronger than towards video-recordings of the same platform, which may increase uncanny feelings towards certain robot platforms in human-robot interaction scenarios. H2, however, states that these initial uncanny feelings would decline when exposing people to a robot for a longer period of time and when giving them access to more proximal behavioral cues. Indeed, H2 can be confirmed by the two studies presented in Section 5.2. In both experiments, people felt most uncomfortable with the robot when judging the still impression of it. Giving a short non-interactive introduction involving speech, facial expressions, and head movements (comparable to watching a short video presentation) already lowered the initial discomfort with the agent significantly (cf. Paper V). A significant influence on the perceived likability and threat could only be measured after the interaction exceeded the time of a typical first impression, suggesting that it takes longer for these perceptual dimensions to be adapted (cf. Paper VI).

Discomfort, threat, and likability are three perceptual dimensions related to the uncanny valley that have often been used interchangeably in the related work. Our findings suggest that they may cover related but separate dimensions of the uncanny valley and differ in the underlying cognitive concepts and thus in their persistence. A feeling of discomfort with the agent may be grounded in people’s uncertainty when it comes to the robot’s abilities and short-term behaviors. This is reflected in the comments participants made about their first impression of the robot in the post-experiment interview. A recurring theme in people’s responses was the difficulty in judging the robot on its physical appearance alone without being able to know what it’s capable of. When giving the two minute long elevator pitch, the robot already displayed all of its expressive capabilities (i.e., speech output, facial expressions, and head movements). Even without giving an insight into its perceptive capabilities, people were able to form a more accurate mental model of what the robot is capable of, which lowered their initial discomfort with it significantly. It thus seems like the initial discomfort is caused by a lack of knowledge about the
agent’s capabilities, which can be lowered by a non-interactive demonstration of its abilities.

The initial judgement of likability and threat, on the contrary, seem to be more persistent and only decreased over a longer conversation with the agent. These dimensions could potentially be more related to uncertainty when it comes to the robot’s long-term behavior and abstract capabilities. Increased likability usually comes with recognizing shared interests and having a good conversational connection that leads to an enjoyable time together. Recognizing these aspects likely takes longer than two minutes. A similar reasoning can be applied to the judgement of threat. With the limited physical capabilities of the Furhat robot, people were not concerned about their physical safety when interacting with the robot. The feeling of threat was possibly more connected to people’s uncertainty when it comes to the robots long-term goals, which, again, requires a longer interaction to form a more valid mental model of the robots internal state.

These findings are important for understanding two dimensions of the uncanny valley. First, the results are an initial indication that uncanny first impressions are connected to the novelty of the stimulus and may not persist in long-term interactions. Second, they demonstrate the necessity of having a closer look at the perceptual dimensions often associated with the uncanny valley. The difference in the persistence of likability, discomfort, and threat shows that caution may be necessary when comparing findings between two studies using different conceptualizations of the uncanny. One important step to allow drawing more conclusions across different empirical investigations in the related work is the agreement on a standard questionnaire to measure uncanny feelings that is usable across different robot embodiments and participants’ language and cultural background.

Given the evidence that interacting with a robot lowers people’s initial uncanny feelings towards it, it is essential to understand what in a robot’s interaction style can accelerate or hinder this process. For this thesis, we decided to specifically focus on the influence of the robot’s personality on the development of people’s uncanny feelings in an interaction (H3). The evidence presented in Section 5.3 can partially confirm H3. While the personality of the robot did influence people’s perception of threat, the data showed no interaction effect between exposure time and personality, as we hypothesized. However, we found that the perceived threat of the two robots differing in their personality-driven behavior only became significant after playing the game with the robot and were rated as comparable after the two-minute social chat. This suggests that the behavior of the robot becomes a more important influence factor for people’s uncanny feelings over time, while the importance of the appearance on people’s perception of the robot declines. For future work, it would be interesting to investigate whether the gap between the two personality intensifies over repeated interactions or whether the two personalities would eventually converge in the threat they elicit.
The finding that the robot’s attitude can generally influence people’s perception of uncanniness is in line with the results reported by Złotowski et al. [153]. However, an important difference in the design of the personalities between this work and the robot personalities utilized by Złotowski et al. exists. In their study, the robot’s attitude was specifically designed to be antagonistic towards the human. Our personalities, on the contrary, were both designed to keep people engaged in the conversation and match the task the robot was placed in. While the impatient robot was meant to be provocative, it mostly vocalized this by showing a constant lack of interest in doing well in the game, thus challenging the human interaction partner to do better. In addition, all utterances being judged as too offensive were filtered out both by crowd-workers on Amazon Mechanical Turk and a researcher involved in the study design. Despite the robot not verbalizing any directly threatening behavior, its personality was still judged as more threatening than the excited and encouraging one. This is especially striking since it was not judged as less likable despite the higher level of threat elicited by it.

One reason for the raise in perceived threat may be that the robot with the impatient personality differed from the expected behavior of an artificial agent, specifically from the behavior of virtual personal assistants people are increasingly used to. Google Home, Amazon Alexa, and Siri have a friendly but reserved attitude towards the conversation partner, which may shape the conversational behavior we expect from a robot. Hence, the robot with the impatient personality might have raised uncanny feelings due to its non-conformance with the initial mental model. However, our findings in the pilot study on Amazon Mechanical Turk point in a different direction: In this study, the robot with the impatient and provocative personality did not differ in perception to a description of the robot without explicitly named personality traits. Only when describing the robot as optimistic and encouraging did people’s perception of the robot personality change. This could suggest that people do not apply mental models formed based on voice assistant technology when being presented with a robot, but rather relate to more machine-like analogies that are not inherently friendly and encouraging. Hence, the impatient and provocative personality may be more representative of the baseline level of threat elicited by robots and, instead of leading to an increased level of threat compared to the baseline, designing an explicitly optimistic and encouraging personality can decrease the baseline level of threat they elicit.

Findings presented in Section 5.3 make two important contributions to our understanding of uncanny feelings: First, they are a further indication that the interaction strategy of the agent has an important influence on people’s uncanny feelings towards a robot. Our data suggest that, in the long run, a robot’s personality and behavior towards the human may even have a greater influence on their perception of it than the appearance of the platform. Second, both personalities of the robot were designed to have a matching level of human-likeness and we found no indication that they differed in this dimen-
sion. Still, we found a different level of uncanny feelings towards the agents with the two different personalities, which cannot be explained by a difference in human-likeness. This finding supports the theory of the uncanny as a multidimensional construct that cannot easily be mapped onto a two-dimensional space [11].

6.1.3 Repeated Exposure and Interaction (H4, H5)

So far, the discussion focused on the development of uncanny feelings within one continuous session of exposure to a robot. From social psychology, however, we know that the mere repeated exposure to a stimulus is sufficient to positively alter people’s perception of it [17, 149]. With H4, we hypothesized that the same effect applies to uncanny robots and that repeated exposure to a robot lowers people’s uncanny feelings towards it. The data presented in Section 5.4 confirms this hypothesis. The extent of exposure to the robot was significantly correlated with their likability towards it and negatively correlated with their feeling of discomfort and threat. These findings further suggest that novelty plays an important role in the formation of uncanny feelings and that an uncanny first impression of a robot may not be representative of people’s future relationship with it.

In our experiment, people were shown the exact same image of the robot during the exposure and rating phase. We can thus conclude that being exposed to the exact type of stimulus significantly decreased people’s uncanny feelings towards it. Several follow-up studies are required to understand how resistant this effect is to changes in the stimuli presentation of the robot. It would, for example, be interesting to vary pictures of the same robot platform in the exposure phase to understand whether it is the exact image people familiarize with or whether it is indeed the robot platform they become acquainted with. A similar study setup can also support a deeper understanding of whether people need to be exposed to the exact robot platform before or whether an exposure to similar types of robots is sufficient to lower their uncanny feelings. Instead of using images of the same Geminoid robot, people could be exposed to a set of other androids. In case exposure to the exact type of robot is necessary, we should not see a significant decrease in uncanny feelings when people are asked about a specific Geminoid robot not included in the exposure set. However, if a similar class of robots can increase familiarity, we should see a decrease in uncanny feelings even if the exact robot image was not seen before. Eventually, such experiments could provide further insights into the characteristics of the novelty that elicits uncanny feelings.

We finally hypothesized that not just repeated exposure but also repeated interaction with a robot would cause a decrease in people’s uncanny feelings towards it (H5). The empirical evidence presented in Section 5.5 supports this hypothesis. The results show that the perception of the robot was altered
in several dimensions in the second and third session people interacted with it. Different perceptual dimensions stabilized at different points in time. For example, the initial perception of competence of the robot gathered after a two minute long social chat persisted over all three interaction sessions. On the contrary, the perceptual dimensions related to uncanniness, discomfort, and threat were the least persistent among the factors we measured. This finding substantially extends initial results presented by Złotowski et al. [153]: They show that uncanny feelings decline not just within a one longer interaction session but further decrease over the course of separate sessions with multiple days of zero exposure in between. Our data also confirm that the days of zero exposure do not harm the process of familiarization with the robot: Even though participants had no access to the robot for several consecutive days, their recall of the robot and their feelings towards it were accurate in most perceptual dimensions.

In this study, we observed a decrease in the perceived threat and discomfort from the first impression to after the first interaction. However, while the discomfort steadily declined after, the perceived threat stabilized between the first and second interaction sessions and only significantly decreased between the second and third session again. This suggests that familiarity is important for reducing both discomfort and threat, and it provides further evidence that novelty may play a different role in the persistence of the two factors. We hypothesized above that discomfort could be related to an initial uncertainty about the agent and its short-term behaviors and capabilities. Findings from the repeated interaction experiment give a slightly different perspective on it. While they do confirm that threat is a more persistent feeling initially and may thus be more concerned with the long-term behavior of the robot, people’s discomfort still declined after the first interaction session, an observation we would not expect if discomfort was only concerned with an uncertainty about the agent’s short-term behavior and expressive capabilities. However, it may still be possible that participants were uncertain whether they had experienced the entirety of expressive behavior the robot was capable of. For example, they could have assumed that the robot’s behavior would change between interaction sessions, for example by using machine learning techniques to adapt the behavior to previously seen users. By keeping the behavior steady over time, people’s trust in the robot’s expressive and perceptive capabilities might have increased, which would explain a further decrease of discomfort even beyond the first session with the robot. Further research is necessary on both the perceptual dimensions to understand the different role they play in the feeling of uncanniness. It would be especially useful to conduct an even longer experiment to understand whether both dimensions stabilize at the same point in time or whether one persists longer than the other. It is even possible that uncanny feelings rebound after a number of interactions with the robot. Given our current understanding of uncanny feelings and the explanatory theories behind the effect, this seems likely only if the robot would drastically and un-
predictably change its behavior. If uncanny feelings would eventually increase even when keeping the robot’s behavior fixed over time, this would be challenging to explain given the current explanatory theories behind the uncanny valley. Hence, a long-term study of several weeks or months could provide further insights into the causes of uncanny feelings.

Another interesting observation from the data presented in Section 5.5 is that the likability of the agent stabilized earlier than discomfort and threat, which suggests that a decreasing level of negative feelings towards the robot does not automatically raise the positive feelings towards it. This, again, supports that caution is required when comparing studies that rely on different concepts to measure uncanny feelings in the related work. Developing a commonly shared understanding of the related perceptual dimensions when measuring uncanniness and the development of a common questionnaire is thus an important future step to deepen our understanding of the uncanny valley.

Our results provide evidence that uncanny feelings may play a sub-ordinate role in long-term human-robot interaction, because the initial discomfort and feeling of threat decrease over time and may eventually be overcome at a certain stage. However, the data also suggest that initial negative feelings towards robots with different face textures decline proportionally, at least up to the third interaction session. In other words, a robot that is initially considered as more uncanny still elicits significantly more uncanny feelings after the third interaction session, even if the severity of the feeling declined. Whether this gap in perception between the two appearances could eventually be closed over the course of more interaction sessions requires further studies. Investigations over an even longer period of time could provide additional insights into the question of whether uncanny feelings eventually vanish completely, leading to a rating of discomfort and threat close to zero, or whether some level of uncanniness would always remain towards certain types of robots.

Undoubtedly, a robot’s uncanny first impression can still have a lasting impact on human-robot interaction if people reject interaction with an uncanny agent altogether, as suggested by Shin et al. [115]. While uncanny feelings could impact people’s decision to purchase a personal robot or a specific type of personal robot, consequences for robots in public spaces may be less severe. Public service robots could, for example, adopt a more proactive strategy to approach potential users. Having the robot opening a conversation could ease the initial burden that might prevents people from initiating an interaction themselves. An interesting question that requires further research is whether the influence of previous experience with robots and artificial agents could lower an initial feeling of discomfort with a novel type of robot. As previously argued, a better understanding of robotic capabilities in general could help with lowering uncertainty with a specific platform at hand. It would be interesting to further examine this, for example by exposing people to several robots over a period of time and measuring their level of discomfort with each new platform. This could eventually lead to a better understanding of whether
novelty with a specific platform, or novelty with the general class of robots and artificial agents causes uncanny feelings. If novelty with robots in general causes uncanny feelings, then interacting with robots in public spaces could be an important bridge to lowering people’s uncanny feelings towards personal robots at home.

In the future, robots will likely not just engage in a single task but will be capable of interacting in a variety of contexts. Another important consideration is thus the influence that familiarity with a specific task has on people’s feeling of novelty towards a robot. More specifically, would people familiarize with a robot faster if they had solved the same task with a human or another robot before? And would the familiarization with the robot be slowed down if a novel task was introduced in a consecutive session with the agent? Ultimately, this results in the question of how fragile people’s mental model of robots is, which is likely something that can be influenced by interaction designers directly. If robots behave predictably and consistently across tasks without sudden changes in their personality, interaction strategy, or task approach, switching between contexts is likely not a challenge to people’s mental model of the robot. If there is little overlap in how the robot behaves in different situations, then uncanny feelings would likely increase at a later stage in the interaction again. The more frequent these behavior changes and the more fluctuating the resulting mental model of the robot becomes, the more difficult it may be for a robot to recover from uncanny feelings. This rule, also known as conformity with user expectations, is well established in human-computer interaction (HCI) and even part of the ISO standard for ergonomics of human-system interaction (ISO 9241) [15]. Hence, building upon already existing knowledge in HCI may be a valuable start for creating robot-specific interaction guidelines. Developing such predictable behavior is also in line with the Guidelines for Trustworthy AI published by the European Commission in 2019, specifically with the guidelines concerning Transparency. This guideline not only notes that a human must always be aware that they are interacting with an AI (and not a human being), it also demands that “system’s capabilities and limitations should be communicated to [...] end-users in a manner appropriate to the use case at hand” [50]. Further research on the influence of novelty in the uncanny and how a robot’s interactive behavior can increase familiarity could thus directly contribute to the development of trustworthy AI in the future.

6.2 Limitations and Future Work

In the following section, limitations of the experimental designs included in this thesis will be discussed. In particular, their implications for generalizing the findings presented in Chapter 5 are reviewed and possibilities for future work to deepen our knowledge on the novelty in the uncanny are proposed.
**Robot Embodiment**

All experiments included in this thesis use the blended robot head Furhat as an embodiment. As argued in Section 4.1, this platform allows us to alter people’s perception between uncanny and likable with minimal confounding factors involved. However, our experiments have also shown that the amount of uncanniness elicited by the robot with the textures we used did not on average exceed the center of the scale. Hence, we can only speculate how the findings presented in this thesis translate to robot platforms on the upper end of the uncanniness scale. For future work, it would be interesting to replicate our experiments with other robots, specifically with full-body platforms that allow for physical manipulation of the environment. With such a platform, it would be possible to further investigate the importance of physical threat and the range of possibilities the agent has to act and manipulate the current situation on people’s uncanny feelings towards robots.

**Participant Demographics**

With two exceptions, experiments included in this thesis have researched uncanny feelings of Computer Science students towards robots. Using such a population poses challenges for the transferability of our findings to a population that is less technophilic. However, it also has advantages beyond the mere ease of availability. Computer Science students are more educated than the general public when it comes to the possibilities and limitations of computer systems and robots. Hence, their expectations towards robots may be more accurate than the mental model of robots that the general public has. This potentially limits the uncanny feelings elicited by our robot platforms. However, our findings also show that merely having a basic understanding of how robotic systems work does not prevent people from feeling eerie towards a specific robot.

Even in the studies included in this paper that did not involve Computer Science students, participants were more exposed to and interested in technology than the general public. In Paper II, researchers and research staff from the Disney Research Lab Pittsburgh participated in the study. While they were not included in or knowledgeable about the specifics of the project, they are still exposed to robotics research in their day-to-day life. Participants for Paper VI were recruited among visitors of the Tekniska Museet Stockholm (Stockholm’s Technology Museum). Hence, it can be assumed that they had at least a strong interest in technology. Even on Amazon Mechanical Turk, almost half of the participants indicated they studied Computer Science or a related subject. Recruiting people for participating in a study involving robots will always be biased and have a higher participation of people with an interest in robotics. For the future, it would thus be interesting to expand research setups in the wild, similar to the one conducted by Rosenthal-von der Pütten et al. [108]. While this limits the control on exposure time, it can give us im-
important insights into the perception of a population more representative of the general public.

The cultural background of participants is another limiting factor in our experiments. All studies included in this thesis have either been conducted in Sweden or the United States of America. While several studies included people from different cultural backgrounds, the sample sizes were too small to thoroughly investigate the differences in responses between them. Culture is expected to play an important role in the perception of uncanniness [93], since the familiarity with robotic stimuli is different already within different countries inside the European Union [119]. Less industrialized countries are expected to have even less access to robots, which will likely increase the novelty factor when meeting robots for the first time. Another influencing factor on the uncanny feelings may be the belief of a soul existing in non-living objects, a belief known as animism, which is still prevalent today and more widespread in some cultures and religions than others [8]. An emphasis on cross-cultural studies in future work could thus provide valuable insights into and extensions to the theoretical explanations behind the uncanny valley.

**Scenario Selection**

Both of the main interactive scenarios developed for this thesis were cooperative and game-based scenarios designed to allow users to meet the robot in a fun and engaging context. To understand more about the uncanny valley in different contexts, it is important to conduct experiments similar to the ones included in this thesis while varying the context the robot is presented in. For example, it is currently unexplored how uncanny feelings evolve over the course of a more task-based interaction with a robot, like buying a train ticket or asking for directions. Since robots will be able to perform several tasks in the future, it would also be important to understand how switching from a familiar task with a robot to an unfamiliar one affects the development of their uncanny feelings towards it.

**Long-term Interaction**

The study included in this thesis on the long-term effect of the uncanny valley was strictly controlled to isolate the factor of repeated interactions from other confounding variables. Hence, repeated interaction with a robot was limited to three sessions, with several days of zero exposure in between. While this substantially expands our understanding of the development of uncanny feelings over time, it still limits the conclusions we can draw for long-term interaction with robots. For the future, it would thus be important to design experiments that allow the measurement of people’s uncanny feelings towards a robot over the period of weeks or months. Several methodological challenges need to be resolved before such an experiment can take place: First, we need to develop measures that rely less heavily on questionnaires. While it may be possible to get people to interact with a robot in a home or work context over a longer
period of time, it may be unfeasible to ask them to report their feelings about the robot on a daily or weekly basis. The fact that measuring uncanny feelings in retrospect does not allow us to understand what in the interaction with a robot elicited a change in people’s perception of it is an even more crucial limitation of questionnaires. Current research on inferring uncanny perceptions from behavioral cues or gaze data that could be gathered unobtrusively and continuously over time has shown promising first results (cf. Section 4.3). However, a deeper understanding of their usability over a longer interaction is necessary before they can be used in long-term interactions.

The second limitation for conducting long-term studies on human-robot interactions concerns the lack of reliable hardware solutions and conversational behaviors that keep people engaged over an extended period of time. Even commercial toy-like platforms, like the NAO robot, are too fragile and require close supervision in research experiments. Blended embodiments or androids are much more expensive, which limits the potential to simply install them in a public space. In addition, they are even more fragile and would thus require extensive technical support throughout the study. Even more severe than the hardware challenges are the limits in engaging interactive behavior. The recent failure of social robotics startups, like Jibo or Cozmo, show that even teams of developers working on a robot interaction for years have trouble designing enough novel content to keep users engaged. Typical research teams have much less resources available, which makes the task even more challenging. Before a continuous measure of uncanny feelings in long-term interactions with robots is possible, it might thus be more feasible to design experiments under close supervision and with controlled exposure time but expand the amount of interaction sessions users have with the robot.

Wizard of Oz Methodology

To limit the influence of errors in the autonomous language understanding and dialogue management unit of the robot, we decided to conduct the experiments presented in Paper VI and VII by remote-controlling the robot. People in our experiments were not aware that the robot was under human control and people who voiced suspicion during or after the experiment were excluded from the data analysis. Furthermore, we used a strict protocol ensuring that the decisions of the robot controller would be as close as possible to the response patterns of the autonomous agent. However, it is still conceivable that remote-controlling the agent and especially the low level of errors resulting from the human control could have influenced our findings. In particular, it is possible that the low error rate and fast response time allowed people to become familiarized with the robot faster because the mental model of a conversation with another human being was more fitting than it usually is when conversing with an autonomous agent. Hence, it is crucial for future work to involve experiments that expose people to the complex autonomous behavior of the robot to understand how this shapes their perception of the robot over time.
**Robot Personalities**

Only two robot personalities, designed to be substantially distinct from each other, were included in studies presented in this thesis. In comparison to the work by Złotowski et al., the personalities were constructed to be realistic and generally engaging for people to interact with [153]. To expand our proof-of-concept, more nuanced personalities should be included in future work. It would also be of interest to further analyze how strongly people’s perception of personalities overlap when it comes to feeling uneasy about them, or whether the eerie feeling is related to people’s own personality and preference. Furthermore, an agent’s conversation style is influenced by more factors than the personality of the robot alone. Other aspects, e.g., the robot’s response time to a user’s input, should also be taken into account in future research.
7. Conclusion

Results discussed as part of this thesis provide evidence that novelty plays an important role in the elicitation of uncanny feelings. Unlike often implicitly assumed, an uncanny first impression may thus not have a lasting impact on human-robot interaction. This finding makes an important contribution to the literature on the uncanny valley, but it is even more substantial for the human-robot interaction community. Our results show that, while uncanny first impressions have an influence on the initial phase of interacting with a robot, the feeling significantly decreases after getting to know it better. Over the course of multiple sessions, uncanny feelings decline even further. Hence, the longer people interact with the agent, the more important its interactive capabilities and interaction strategies seem to become in shaping people’s overall perception of it. This suggests an important future research strand that has found little consideration in the research related to the uncanny valley so far: If the practical impact of uncanny feelings on human-robot interaction is low because the initial perception is eventually overturned by an interactive impression, it might be more sustainable to focus on studying interaction strategies that artificial agents can use to help people familiarize with them efficiently and thus overcome initial uncanny feelings towards them more quickly. Even in the embodied interaction community, there are still substantial gaps when it comes to understanding what impact conversational patterns have on human perception of artificial agents. Ideally, future research could develop interaction guidelines for robots and artificial agents that help them to accelerate the process of familiarization for unacquainted users.

While HRI researchers can build upon existing design principles developed in human-computer interaction to define interaction guidelines to overcome uncanny feelings, findings presented in this thesis may also be insightful for the HCI community in general. Data gathered across several experiments presented in this thesis suggest that novelty in robots can negatively impact people’s feelings towards a platform. The concept of novelty has gained substantial attention in human-computer interaction already. However, it was mostly considered with a positive sentiment, leading users to experience initial excitement about a new technology that wears out over time [27]. Our results suggest that novelty may be more complex and can also lead to insecurity and consequently to reluctance using a new technology. The difference between novel software solutions and novel robot systems may stem from the amount of previous experience people have with similar systems. While new software can still create a novel user experience, users have gathered extensive experience with different software solutions by now, which helps them to manage
expectations with the new system at hand. When it comes to robots, such experience is lacking, which may consequently lead to uncanny feelings instead of excitement. However, uncanny feelings may still arise in other areas of human-computer interaction unrelated to robotics. When developing novel computer device (e.g., virtual reality devices [84]) or input interfaces that are unlike anything previously known, similar uncanny feelings may be elicited. In this case, findings from uncanny valley related research can be considered to help users overcome their initial uncanny perception towards the new device.

With its focus on uncanny feelings in interactive scenarios, this thesis can additionally contribute to the explanatory theories behind the uncanny valley. In Section 4.1, we discussed that findings from our choice of robot platform support the perceptual mismatch theory more strongly than the categorization ambiguity theory, since uncanny feelings are elicited despite the platform’s clear affiliation with the category of mechanical devices. The contribution of this thesis, however, goes beyond the study of the robot’s appearance. The core finding is that uncanny feelings decline over time, not just within one interaction session, but also across multiple sessions with several days of zero exposure in between. This could potentially support both the categorization ambiguity and the perceptual mismatch theory. Longer access and exposure to a robot’s full behavioral stream adds potential to resolve ambiguities between two categories. At first glance, our findings are contradictory to the perceptual mismatch theory, since an exposure to a co-present robot which reveals all its multimodal capabilities should allow more potential for a perceptual mismatch to arise and hence increase uncanny feelings. The longer people are exposed to a robot, however, the more potential they have to update their initially incomplete and inaccurate mental model of the robot. Our results suggest that an increase in familiarity could help with correcting people’s mental model of a robot and lead to more accurate expectations towards it, which consequently leads to a decline in people’s uncanny feelings and hence supports the perceptual mismatch theory.

We could further show that the personality of the robot itself can elicit uncanny feelings. This strongly supports the notion that the uncanny valley is a multidimensional concept that involves more perceptual dimensions than the robot’s human-likeness alone [11]. In this case, we did not create a mismatch in the level of human-likeness within the different interaction styles of the robot. However, we created a personality very atypical for a robot, which caused a potential mismatch in expectations created based on the robot’s appearance. This finding is important for robot designers in general, who need to pay close attention to unintentional incongruence when designing a robot’s embodiment and interaction. Further research is necessary, however, to understand whether a mismatch in any perceptual dimension can cause an uncanny feeling or whether this is limited to certain perceptual aspects.
Summary in Swedish

Robotar blir allt mer förekommande i det offentliga livet. Enligt en studie från Europeiska Kommissionen från 2012 har 12% av den europeiska befolkningen haft personlig kontakt med en robot hemma eller på jobbet. I en ny studie som genomfördes som en del av denna avhandling rapporterade 22,5% av de amerikanska deltagarna att de har en robot hemma och 23,8% av deltagarna har eller har haft tillgång till en robot på sin nuvarande eller tidigare arbetplats. även om dessa studier inte är direkt jämförbara, så visar de en trend i tillgängligheten för robotar i dagliga livet: Teknologier såsom autonomna dammsugare eller robotgräsklippare blir inte bara mer pålitliga och robusta, de blir också överkomliga för folk i allmänhet. En liknande trend kan observeras hos virtuella personliga assistenter, som nu finns i fler och fler privata hushåll. Tjänsterobotar och socialassistenter utvecklas fortfarande parallellt. Målet med social robotik är dock att förena denna utveckling och designa robotar som kan assistera med dagliga aktiviteter samt kommunicera på en socialt acceptabel nivå.


Relaterade arbeten med uncanny valley effect har mest fokuserat på människans första intryck av robotarna. I de flesta studier såg deltagarna roboten bara i några sekunder innan de utvärderade den. Bedömningarna baserades vanligtvis entart på robotens fysiska utseende, eftersom studierna inte gav någon möjlighet att interagera med plattformen. Den här avhandlingen handlar om huruvida den kusliga känslan utlöst av det första intrycket av en väldigt mänsklig robot kvarstår i mer långvariga interaktioner. Flera interaktiva scenarier och motsvarande verbala och icke-verbala robotbeteenden har utvecklats och programmerats för att belysa på denna fråga.

Resultaten från de olika studier som förklaras mer detaljerat i avhandlingen skapar tvivel om effekten av uncanny valley verkligligen består över tid. Det visar

Detta arbete utgör ett viktigt bidrag till forskningen om människa-robot-interaktion eftersom det visar den begränsade praktiska effekten av *uncanny valley*. Till skillnad från implicita antaganden som uttrycks i litteraturen, verkar initiala känslor av obehag inte ha några bestående effekter på förhållanden mellan människor och robotar. Hittills har det visat sig vara svårt att helt undvika de kusliga känslor som utlöses av en robot. I stället för att fokusera på att minska framkallandet av obehagliga känslor i första hand kan det alltså vara en mer framgångsrik strategi att utforma interaktioner som hjälper människor att snabbt lära känn en robot och därmed övervinna de ursprungliga obehagliga känslorna mot den.


Auf dem Forschungsgebiet des uncaly valley lag der Fokus bisher auf dem ersten Eindruck eines Roboters. In den meisten Studien sahen Versuchspersonen den Roboter für nur wenige Sekunden, bevor sie gebeten wurden diesen zu bewerten. Einschätzungen basierten dabei in der Regel ausschließlich auf dem äußeren Erscheinungsbild, da die Studien keine Gelegenheit zu einer Interak-


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