Legibility of Robot Behavior : A Literature Review

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Abstract

The objective of the work at hand is to give an overview of the work done so far regarding legible robot behavior. Legibility roughly means that a person intuitively understands the intentions of a robot. To this end, we systematically reviewed 32 articles published in the primary HRI publication venues. The purpose of the following review is to answer the questions: How do other researchers define legibility?, How can legibility be measured? How can one implement legible robot behavior?, and Which factors are correlated with legibility?

Introduction

Robots will increasingly become part of the habitats and work spaces of humans. Not only the Google self-driving car will cross our paths on the street, robots will assist industrial workers in factories as co-workers, support care attendants in nursing homes or hospitals, help customers in a supermarket, or do the housework in our homes. They will cross our paths, hand-over objects, assist us in various ways, they will interact with us. Therefore, we have to look at the factors that determine a positively perceived interaction. Heerink, Krose, Evers, and Wielinga (2009) proposed several indicators for socially accepted robot behavior like perceived enjoyment, perceived sociability, perceived ease of use, social presence, etc. Furthermore, Bartneck, Kulić, Croft, and Zoghbi (2008) stated the five key concepts in HRI: anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety. From our point of view, another important factor of a positively perceived interaction is legibility, which roughly means that an interacting human is able to understand the robots intentions. For example, imagine a robot performing some household chore, such as preparing a meal. The robot fulfills its duty, but manipulates objects with sudden, unpredictable movements. It rushes through the kitchen with rapid changes of direction or ignores obvious errors like a pot not being placed properly on the stove. It opens the tap before getting the pot to fill the water in. One would be irritated by the robot, an effective and efficient interaction is hardly possible. In short one would not accept such an unpredictable robot. Furthermore, our assumption - that legibility is an important HRI factor[1] - is supported by an finding of a study Dautenhahn et al.

[1] As HRI factors we determine all variables indicating (1) how a human-robot interaction was perceived by the human interactor or (2) how we can assess an interaction.

(2005) conducted to explore peoples' perception towards the future use of robot companions. They found that one important aspect of robot behavior is predictability.

Due to the novelty of the topic of legible robot behavior and the novelty of the emerging field of Human Robot Interaction (HRI) no generally accepted definition or guidelines have been proposed so far. Rather, the objective of the following is to find out what other researchers in the HRI community have published regarding legible robot behavior in order to extract a general definition as well as further interesting facts about legibility like methods to measure legibility, or how legible behavior can be generated and what needs to be considered. Another interesting aspect is to investigate which other acceptance measures (Heerink et al., 2009) or HRI concepts (Bartneck et al., 2008) are correlated with legibility. To this end, we conducted a literature review where we systematically investigated articles regarding the following research questions:

- How is legibility defined? Which terms are used synonymously?
- How is legibility measured? What research methods have been used to investigate legibility?
- How can legible robot behavior be realized?
- Which HRI factors are correlated by legibility?

Review Protocol

In order to find all publications related to what we define as "legibility of robot behavior" we searched the ACM Digital Library[2] and IEEExplore Digital Library [3]. Additionally we used the literature search engine "Web of Knowledge" [4] to take into account a wide range of journals. From our previous work and former literature research we know that other authors describe, what we call legibility, with terms like readability (Takayama, Dooley, & Ju, 2011), anticipation (Gielniak & Thomaz, 2011), or simply predictability (Bortot, Born, & Bengler, 2013) of robot behavior and motion. Based on this knowledge we determined the following search terms to find publications concerning legible robot behavior:

- legibility/legible AND motion/behavior AND robot
- readability/readable AND motion/behavior AND robot
- anticipatory/anticipate AND motion/behavior AND robot
- predictability/predictable AND motion/behavior AND robot

After a first selection process where we removed all non related publications[5] we found 32 publications dealing with legibility of robot behavior (Dautenhahn et al., 2005; Nehaniv et al., 2005; Dautenhahn et al., 2006; Kirsch, Kruse, & Mösenlechner, 2009; Kirsch et al., 2010; Beetz et al., 2010; Kruse, Kirsch, Sisbot, & Alami, 2010; Dehais, Sisbot, Alami, & Causse, 2011; Eyssel, Kuchenbrandt, & Bobinger, 2011; Gielniak & Thomaz, 2011; Takayama et al., 2011; Lichtenthäler, Lorenz, & Kirsch, 2011; Basili, Huber, et al., 2012; Lichtenthäler, Lorenz, Karg, & Kirsch, 2012; Kruse, Basili, Glasauer, & Kirsch, 2012; Lichtenthäler, Lorenz, & Kirsch, 2012; Dragan & Srinivasa, 2013; Dragan, Lee, & Srinivasa, 2013; Bortot et al., 2013; Sisbot et al., 2005; Sisbot, Marin-Urias, Alami, & Simeon, 2007; Alami, Clodic, Montreuil, Sisbot, & Chatila, 2006; Sisbot,

[2]ACM: `http://dl.acm.org/`

[3]IEEE: `http://ieeexplore.ieee.org`

[4]Web of Knowlege: `http://apps.webofknowledge.com`

[5]e.g. publications where the search terms are not related to each, like motion does not refer to robot motion and predictable refers to a statistical test. Sometimes the term legibility refers to a figure, or the topic was human intention recognition

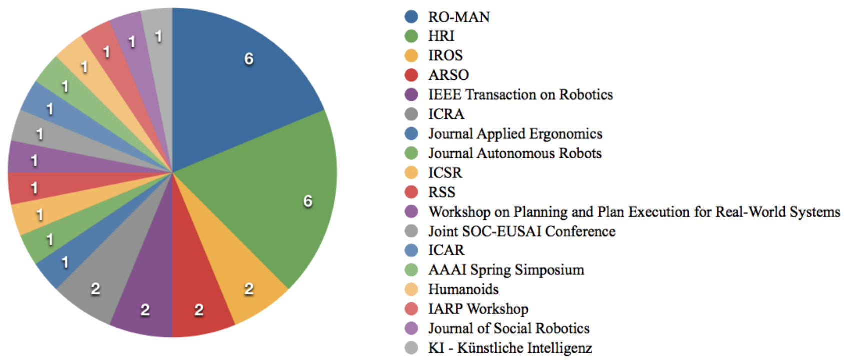


Figure 1. Pie Chart showing the distribution of legibility articles in the HRI publication venues. A high ratio (12 of 32) appeared in proceedings of the ACM International Conference on Human-Robot Interaction (HRI) and IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN).

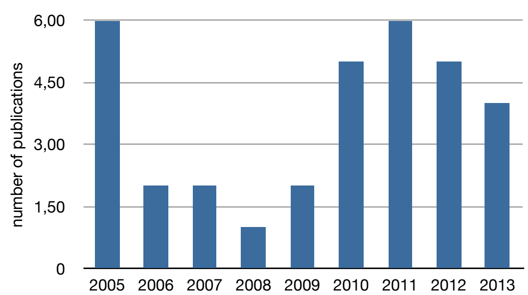


Figure 2. Histogram showing the distribution of legibility articles over the last eight years (2005-2013).

Clodic, Alami, & Ransan, 2008; Sisbot, Marin-Urias, Broquere, Sidobre, & Alami, 2010; Mainprice, Sisbot, Siméon, & Alami, 2010; Mainprice et al., 2011; Sisbot & Alami, 2012; Guzzi, Giusti, Gambardella, Theraulaz, & Di Caro, 2013; Lichtenthäler et al., 2011, 2012; Lichtenthäler et al., 2012). As mentioned before he authors partly use other notations for what we denote as legibility. Most of the authors (21) are using the term legibility (Alami, Clodic, Montreuil, Sisbot, & Chatila, 2005; Clodic, Fleury, Alami, Herrb, & Chatila, 2005; Sisbot et al., 2005; Clodic, Montreuil, Alami, & Chatila, 2005; Sisbot, Marin-Urias, et al., 2007; Alami et al., 2006; Sisbot et al., 2008, 2010; Mainprice et al., 2010, 2011; Dehais et al., 2011; Sisbot & Alami, 2012; Kirsch et al., 2010; Kruse et al., 2012, 2010; Kirsch et al., 2009; Lichtenthäler et al., 2011, 2012; Lichtenthäler et al., 2012; Beetz et al., 2010; Guzzi et al., 2013; Dragan et al., 2013; Dragan & Srinivasa, 2013) a few (5) are using predictability (Dautenhahn et al., 2005, 2006; Basili, Huber, et al., 2012; Eyssel et al., 2011; Bortot et al., 2013), one is using the term anticipatory (Gielniak & Thomaz, 2011) and one is using the term readability (Takayama et al., 2011).

As shown in Fig. 1 a high ratio of the publications were published in the Proceedings of the Human-Robot Interaction Conference (HRI) and the International Symposium on Robot and Human Interactive Communication (RO-MAN). The first articles dealing with legibility were published in 2005. The histogram in Fig. 2 shows the distribution of publications over the time.

Results of the Literature Research

In the following we first give a brief overview of the reviewed articles by summarizing the content of each publication. Afterwards we report our findings regarding the aforementioned questions.

Summary

We start our summary with a list of the articles where legibility is only briefly mentioned as an important factor or new challenge for HRI (Clodic, Fleury, et al., 2005; Nehaniv et al., 2005; Clodic, Montreuil, et al., 2005; Dautenhahn et al., 2005, 2006; Bortot et al., 2013). For example Clodic, Montreuil, et al. (2005) wrote: *"One major key point is that the robot must act in a way judged as legible and acceptable by humans."* Furthermore, one finding of a study Dautenhahn et al. (2005) conducted to explore people's perception towards the future use of robot companions was that the behavior of a robot has to be predictable (= legible). As a main result they state, that *"a future robot companion would need to be predictable, controllable, considerable and polite"* (Dautenhahn et al., 2005).

A vast amount of work was published by researchers from the Robotics and Artificial Intelligence Group at LAAS/CNRS in Toulouse, France, headed by Rachid Alami (Alami et al., 2005; Clodic, Fleury, et al., 2005; Sisbot et al., 2005; Clodic, Montreuil, et al., 2005; Sisbot, Marin-Urias, et al., 2007; Alami et al., 2006; Sisbot et al., 2008, 2010; Mainprice et al., 2010, 2011; Dehais et al., 2011; Sisbot & Alami, 2012). One goal of the group is the development of a human aware motion and manipulation framework, which synthesizes safe, comfortable, socially acceptable, and legible motions. Therefore, the main topic of the publications from this group is the development, implementation and evaluation of such a system, which consists of a Human-Aware Navigation Planner (HANP) (Sisbot et al., 2005; Sisbot, Marin-Urias, et al., 2007), generating legible paths, and a Human-Aware Manipulation Planner (HAMP) (Sisbot, Marin, & Alami, 2007; Sisbot et al., 2008, 2010; Mainprice et al., 2010, 2011; Sisbot & Alami, 2012), performing legible hand-over tasks. They have integrated cost functions modeling human comfort, safety, and visibility in their navigation and motion planning system in order to generate comfortable, safe and visible motions. The cost functions are partly based on the findings of the human-robot experiments conducted by Dautenhahn et al. (2005, 2006). An evaluation of HAMP using psychophysiological measures was conducted by Dehais et al. (2011). Furthermore, some work was done towards a Human-Aware Task Planner (HATP)(Alami et al., 2005, 2006) which should generate legible high level robot task plans.

Kruse et al. (2010) extended the aforementioned Human Aware Navigation Planner (Sisbot, Marin-Urias, et al., 2007) by relaxing some constraints and changing cost functions in order to exploit the fact that humans might act cooperatively and make way for the robot, which should increase the legibility of HANP. Another approach to increase the legibility of HANP was also proposed by Kruse et al. (2012). They assume that human-like behavior leads to a higher legibility. Therefore, they added an additional cost function to HANP in order to produce navigation behavior similar to the behavior humans show in a human-human path crossing experiment (Basili, Sag, et al., 2012). Also Guzzi et al. (2013) followed the "human-likeness increases legibility" assumption and introduced a navigation algorithm based on simple obstacle avoidance heuristics modeling pedestrian behavior. Another implementation of this "human-likeness increases legibility" assumption is found in Beetz et al. (2010). They use a dynamic movement primitive approach to mimic human arm trajectories. Furthermore, their proposed method for mobile manipulation should generate more stereotypical motions and behavior, which, according to their assumption, leads to a more legible behavior.

A high level joint-task planning framework was proposed by Kirsch et al. (2009). Their assumption is that robot plans must take into account human preferences and abilities in order to generate legible plans. Therefore, they present an integrated planning and learning framework. Kirsch et al. (2010) described several planning and action-related HRI problems like collaborative planning, navigation and joint manipulation and pointed out the challenges. One challenge they point out is to achieve legible robot behavior. Furthermore, they claim that *"legibility is a prerequisite to establish human comfort"* and that *"Legibility is connected to the perceived safety and comfort"*.

Despite the promising results of the aforementioned methods and approaches legibility has not been objectively evaluated. Only the Human-Aware Manipulation Planner (Sisbot, Marin-Urias, et al., 2007) HAMP was tested regarding legibility in an experiment conducted by Dehais et al. (2011). The aforementioned work is not only focussing on legibility, other factors like comfort, social acceptability, and safety are also taken into account (e.g. (Sisbot, Marin-Urias, et al., 2007; Sisbot & Alami, 2012; Kruse et al., 2010; Guzzi et al., 2013)). To conclude, in the work presented so far the authors either model social constraints, human preferences and abilities and/or mimic human motions in order to generate legible as well as comfortable, safe and socially acceptable robot behavior.

The work from Dragan et al. (2013); Dragan and Srinivasa (2013), and Gielniak and Thomaz (2011) is focusing explicitly on generating legible motions. Both present a method to generate legible motions as well as an evaluation method to test the proposed method regarding legibility. Gielniak and Thomaz (2011) presents an algorithm to increase the legibility of a given gesture. In their work a legible motion is determined as anticipatory motion. Dragan et al. (2013) present a mathematical definition and model for goal directed legible arm motions. In their work the authors distinguish between legibility, which is defined as the ability to anticipate the goal and predictability, which is defined as the ability to predict the trajectory. This distinction is very different to the comprehension about legibility of all the other authors presented in this review. Furthermore, additionally to the proposed model to generate legible as well as predictable goal directed robot arm motions Dragan et al. (2013) presented the design and results of experiments where legibility as well as predictability were measured. Their experimental results support their hypothesis that legibility and predictability are contradictory properties of a motion.

In the following we elaborate on the experiments measuring legibility in human-robot interaction and then subsequently present our own published work on legibility. Eyssel et al. (2011) investigated the effect of predictability on anthropomorphism and acceptance of a robot in a video based experiment. They found no significant correlation between predictability and anthropomorphism, but a significant correlation between predictability and acceptance. Takayama et al. (2011) used animation techniques in order to let the robot show forethought. They assume that showing forethought would increase the readability (= legibility) of robot behavior and also influence the perception of the robot. They presented the design and the results of a video-based experiment measuring legibility and other factors like intelligence and safety. Results could not support their hypothesis that forethought increases legibility, but they could show that *"forethought makes people more sure of their interpretations of robot behavior, and make the robot seem more appealing and approachable."* One real-live experiment was conducted by Basili, Huber, et al. (2012). The participants had to predict the goal of an approaching robot. The experimental design is similar to the experiments presented by Dragan et al. (2013); Dragan and Srinivasa (2013), however in (Basili, Huber, et al., 2012) the robot mimics human motions. Basili, Huber, et al. (2012) compared the human-robot results with the results of a human-human experiment and found out that although the robot behaves the same way as humans the ability to predict the goal of the robot was three-fold below the human-human results. The experiment conducted by Bortot et al. (2013) supports the assumption stated by Beetz et al. (2010), that stereotypical motions, which are more predictable than variable motions, are leading to increased human well-being. Nevertheless, legibility was not measured in the experiment. In our own work regarding legibility (Lichtenthäler et al., 2011, 2012; Lichtenthäler et al., 2012) we first introduced a framework to measure legibility in human-robot interaction (Lichtenthäler et al., 2011) and presented the design and results of two different experiments where we measured legibility and other factors like comfort, reliability and perceived safety of state-of-the-art navigation methods.

One interesting thing we want to point out is that a vast amount of early work in the field of legible robot behavior was done within the COGNIRON project `http://www.cogniron.org` (Dautenhahn et al., 2005; Alami et al., 2005; Clodic, Fleury, et al., 2005; Nehaniv et al., 2005; Clodic, Montreuil, et al., 2005; Sisbot et al., 2005; Dautenhahn et al., 2006; Alami et al., 2006; Sisbot, Marin-Urias, et al., 2007; Sisbot, Marin, & Alami, 2007; Sisbot et al., 2008). The earlier mentioned human aware motion and manipulation planner and the studies conducted by Dautenhahn (Dautenhahn et al., 2005, 2006) were an outcome of the COGNIRON project. Based on our review we can claim that the COGNIRON project was an important starting point for legibility as an HRI key factor and the development of methods providing legible robot behavior.

How is Legibility Defined?

A first definition of legibility was given by Nehaniv et al. (2005). Legibility is defined as "*making the robots actions and behaviour* ***understandable*** *and* ***predictable*** *to a human*". Clodic, Fleury, et al. (2005) stated that a robot "*needs to be able* ***to explain its task*** *by exhibiting a legible behavior*". Similar to the aforementioned definitions is the definition given in (Sisbot, Marin-Urias, et al., 2007; Alami et al., 2006), where the authors wrote that *"a motion is legible when a human partner can easily* ***understand*** *the robot's* ***intentions*** *by observing its motions"* which is in turn very similar to the definition from Kirsch et al. (2010) *"We use the term legible to describe behavior that is intuitively* ***understood*** *by humans."* Sisbot and Alami extended this definition in (Sisbot et al., 2010; Sisbot & Alami, 2012) and stated: *"The human partner should* ***understand*** *clearly the* ***intention*** *of the robot* ***without further communication."*** A more specific definition regarding legibility of robot motions is given in (Basili, Huber, et al., 2012): *"The human is able to* ***attribute goals*** *and* ***predict*** *motion* ***trajectories"*** and in (Beetz et al., 2010) *"humans can regognize the intentions of the motion."* Another definition regarding legible robot motion is given by Guzzi et al. (2013). They state that a legible motion means that *"a person observing robot motion can intuitively* ***understand the spatial target*** *the robot is heading to"*. Furthermore, another definition in the same line is given in (Sisbot & Alami, 2012) *" With a legible motion, the robot must* ***make clear its intention"*** or in (Kruse et al., 2012, 2010) *"legibility means that an ordinary, uninstructed person can* ***understand*** *and* ***anticipate*** *the robots* ***actions****."* Our own definition of legibility conforms to the definitions stated so far. In (Lichtenthäler et al., 2011, 2012) we define that *"robot behavior is legible, if a human can* ***infer*** *the next* ***actions, goals*** *and* ***intentions*** *of the robot with high accuracy and confidence"*, which is extended in (Lichtenthäler et al., 2012) with *"and the robot behavior* ***fulfills the expectations*** *of a human interaction partner."*

Another aspect of legibility was pointed out by Takayama et al. (2011). In addition to the aforementioned factors of legible robot behavior, understandability and predictability Takayama et al. (2011) adds the factor **effectiveness** stating that robot behavior is legible - in their work they call it readable - when *"people can figure out what the robot is doing, reasonably* ***predict*** *what the robot* ***will do next****, and ultimately interact with the robot in an* ***effective way****"*.

The definition given by Gielniak and Thomaz (2011) refers to communicative gesture motions, which are passing a specific message. They state that a legible, they call it anticipatory, motion is an **intent expressive** motion, meaning that a human is able to **understand** the communicated **message**.

According to the aforementioned definitions of legibility we can conclude the following factors defining legible robot behavior:

- understandable intentions ((Takayama et al., 2011; Lichtenthäler et al., 2011, 2012; Kruse et al., 2012, 2010; Nehaniv et al., 2005; Clodic, Fleury, et al., 2005; Sisbot, Marin-Urias, et al., 2007; Alami et al., 2006; Kirsch et al., 2010; Sisbot et al., 2010; Sisbot & Alami, 2012; Beetz et al., 2010; Sisbot & Alami, 2012))
- understandable message ((Gielniak & Thomaz, 2011; Nehaniv et al., 2005))
- predictable actions ((Takayama et al., 2011; Lichtenthäler et al., 2011, 2012; Lichtenthäler et al., 2012; Kruse et al., 2012, 2010; Nehaniv et al., 2005))
- predictable motion trajectories ((Nehaniv et al., 2005; Basili, Huber, et al., 2012))
- predictable goals ((Guzzi et al., 2013; Lichtenthäler et al., 2011, 2012; Nehaniv et al., 2005; Basili, Huber, et al., 2012))
- fulfills expectations ((Lichtenthäler et al., 2012))
- effective interaction ((Takayama et al., 2011; Guzzi et al., 2013))

Only Dragan et al. (2013); Dragan and Srinivasa (2013) deviate from these common definitions and present a new and very interesting finding regarding legible grasping motions. In their work they differentiate between legibility, which is defined as the ability to anticipate the goal, and predictability, which is defined as the ability to predict the trajectory. We will discuss this distinction in section .

From the definitions that most researchers agree on, we want to extract a compact definition of legibility in the following. For this common definition we first summarize the above mentioned factors. The term *understandable intentions* includes the factors *understandable message, predictable action, predictable motion trajectory* and *predictable goal*. Because, if the human observer or interactor understands the robots' intentions - meaning the human understands what the robot is going to do, knows its plans and purpose, and anticipates the outcome - then the ability to predict actions, trajectories, and goals is included. Furthermore, when the human observer understands the intention of a gesture, then he/she understands the message, the robot wants to communicate. Therefore, we claim that *understandable intention* is an umbrella term for all these factors. The factor effective interaction can more be seen as a correlated factor of legibility. Effectivity is more a consequence of legible behavior and not a factor defining legibility. Therefore, we exclude *effective interaction* from our common definition and shift this factor to the *correlated factors*. To conclude, after summarizing and excluding factors defining legibility we end up with the two factors *understandable intentions* and *fulfills expectations*. Out of this we derive the following definition of legible robot behavior:

Definition 1 (Legible Robot Behavior)**.** *Robot behavior is legible if: (Factor 1) a human observer or interactor is able to understand its intentions, and (Factor 2) the behavior met the expectations* *of the human observer or interactor.*

How is Legibility Measured?

Methods to measure legibility are described in 12 publications. In the following we will give an overview of the presented methods and briefly report the results. Within this review we only concentrate on the methods to measure legibility and disregard the measurement of other factors.

In the study presented by Dautenhahn et al. (2005) the participants were asked about their desires for a future robot companion. Among other factors the participants were directly asked to rate how predictable a future robot should be on a 5-point likert scale. No specific robot behavior was evaluated. Most participants (54%) wanted a high predictable or predictable (36%) robot behavior, only 11% were neutral about the potential predictability. These results show us how important the factor predictability and therefore legibility is for the development of robot behavior.

In the experiments presented in (Eyssel et al., 2011; Bortot et al., 2013) predictability was used as an independent variable in order to investigate correlations. Eyssel et al. (2011) conducted an experiment in order to investigate the correlation between predictability and anthropomorphism as well as acceptance. They showed the participants a video in order to introduce the robot. The video was followed by a short description. By chance the participants got one of two different descriptions manipulating the perceived predictability of the robot. However, high predictable or low predictable robot behavior was imagined by the participants and not implemented. Hence, again no specific robot behavior was evaluated. After seeing the video the participants were asked to complete a questionnaire with questions measuring anthropomorphism and acceptance. They did not find a significant correlation between predictability and anthropomorphism, but they could show a correlation between predictability and acceptance. A real life experiment using an industrial robot arm was conducted by Bortot et al (Bortot et al., 2013) to investigate the influence of the arm trajectory on user well-being and performance. They hypothesized that a variable trajectory (= unpredictable) leads to lower results in performance and well-being. They tested this hypothesis in an experiment where the participants had to solve two different tasks while sitting at a workbench. The robot arm moved in five different conditions, whereby one condition was the unpredictable condition (=variable), see Fig 3. Human performance and well-being were measured by evaluating the task performance and by using the NASA-TLX[6] (Hart & Staveland, 1988), STAI-S (Spielberger, 2010) questionnaires as well as subjective evaluations. Results supported their hypothesis. Therefore, we can conclude that a stereotypical motion leads to higher performance and human-well being.

The aforementioned Human Aware Motion Planner (HAMP) was evaluated by Dehais et al. (2011). They tested three different motion trajectories (HAMP vs. HAMP without grasp detection vs. No HAMP) in a human-robot hand over task. After each hand-over the participants were asked to rate legibility, as well as safety and comfort on a 9-point visual analog scale. Additionally to the questionnaires they used also psychophysiological measures (skin conductance, EMG, occulometry) in order to get objective measures for comfort and safety. As hypothesized by the authors the HAMP trajectory revealed the best results from the ratings as well as from the psychophysiological measures and from the results we can assume a correlation between legibility, safety and comfort.

In (Gielniak & Thomaz, 2011; Dragan et al., 2013; Dragan & Srinivasa, 2013) the authors let the participants predict the intention of a robot motion and used the prediction time to measure legibility of developed methods following the assumption that a shorter prediction time indicates

[6]NASA-TLX: http://humansystems.arc.nasa.gov/groups/TLX/index.html

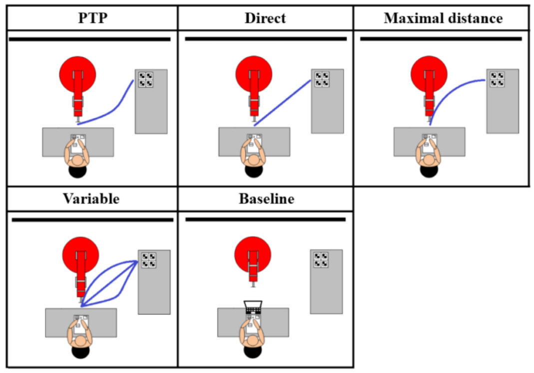


Figure 3. Design of the experiment conducted by Bortot et al. (2013) in order to investigate the influence of the robot arm trajectory human on performance and well-being. (Picture taken from Bortot et al. (2013))

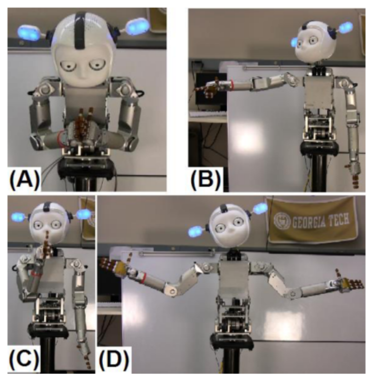


Figure 4. Example of gestures used in the experiment conducted by Gielniak & Thomaz, 2011 in order to validate their proposed method to increase legibility of a given communicative gesture. The pictures are showing the gestures (A) Bow (B) Point (C) Shhh... (D) I Dont Know. (Picture taken from (Gielniak & Thomaz, 2011).

a higher legibility. The purpose of the experiment Gielniak and Thomaz (2011) conducted was to verify that their proposed algorithm increases the legibility of a given gesture, see Fig. 4. They showed the participants videos of six different communicative gestures (beckon, stop, I don't know, wave, point, bow) performed by a robot, randomly either the original gesture or the modified gesture. The participants were instructed to press a button immediately when they feel certain to predict the meaning of the gesture. The time the participants need to anticipate the gestures meaning was measured. They could show that their method increases legibility of a communicative gesture. Dragan et al. (2013); Dragan and Srinivasa (2013) differentiate between legibility and predictability and proposed two models generating either legible or predictable robot arm motions. Therefore, the objective of their experiments was to evaluate the proposed models (Dragan et al., 2013) and to evaluate model parameters (Dragan & Srinivasa, 2013). In both publications the method is equal. To measure the legibility they used a video based method similar to the aforementioned experiments. (Dragan et al., 2013) showed their participants videos of different robot arm trajectories (see Fig. 5) towards one of two goals. They asked the participants to stop the video as soon as they felt confident

Figure 5. Experimental setup presented by Dragan et al. (2013). They showed the participants videos of a robot arm performing different trajectories towards one of the two goals and asked the participants to stop the video by pressing a button as soon as they felt confident to predict the goal. (Picture taken from Dragan et al. (2013)).

to predict the goal and measured the prediction time. This methodology to measure legibility is also used by (Gielniak & Thomaz, 2011). (Dragan et al., 2013) combined the time measure and correctness of the goal prediction to one score measure: guessing wrong gets a score of 0, and guessing right gets a higher score if it happens earlier. Predictability was measured by asking the participants to draw the expected trajectory and showing them the trajectory videos and asking them to rate how much the behavior met their expectations. Results showed that, according to their definitions, predictable trajectories and legible trajectories are different.

In the following we present experiments where participants were asked to predict the robot's intention. In this case a high rate of correct predictions indicates a high legibility. A real world experiment was conducted by Basili, Huber, et al. (2012). They address the question if a motion is more predictable when a human or a robot is performing it? Therefore they tested three different conditions, (1) a human wearing sunglasses and a scarf to avoid gazing effects, (2) a human with gazing effects, and (3) a robot. All three were performing similar motions. The experimental setup is depicted in Fig. 6. The participants were placed by chance on one of the three target positions (see Fig. 6) and the human/robot is either heading towards them or to another target. The participants were asked to predict as soon as possible whether or not the human/robot was to approach the participant. Results show that the legibility was higher for the two human conditions. The ”gaze” condition scored with 98.9 % correct answers, ”no gaze” with 93.55% and the robot condition with 81.25 % correct answers. Takayama et al. (2011) conducted an experiment to address the question: does the use of animation principles to show forethought make the robot behavior more legible and how does it influence people's perception of robots? The authors also tested whether showing goal-oriented responses influenced people's perception, but this is irrelevant for our legibility review. They prepared simulated videos of a robot performing four different tasks (opening a door, delivering a drink, ushering a person into a room, requesting help from a person to plug into an outlet) either showing forethought or not (see Fig. 7). The videos were divided into two parts, the first part shows the behavior of the robot before the robot actually opens the door, delivers the drink, asks for help, or directs the person. The second part shows the rest of the task. In their online study the participants saw the first part of the video and were asked to predict the robot's intentions and how

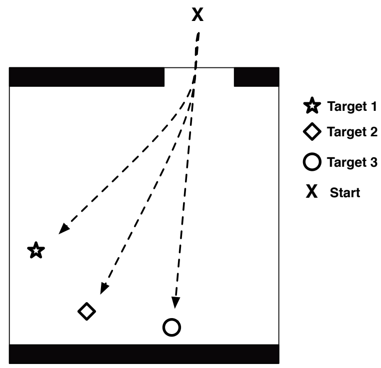


Figure 6. Experimental Setup from an experiment conducted by Basili, Huber, et al. (2012). The participant were placed on one target and the human or robot is either approaching the participant or another target.(Picture based on Basili, Huber, et al. (2012)).

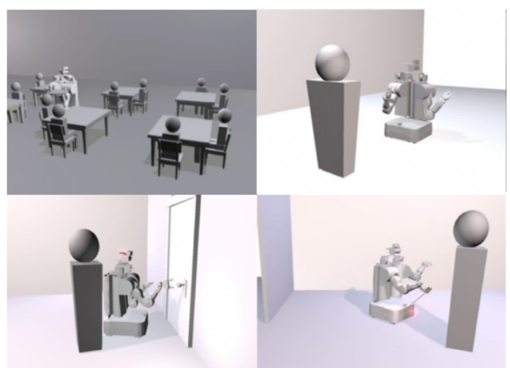


Figure 7. Experimental Setup from an experiment conducted by Takayama et al. (2011) in order to investigate if showing forethought increases legibility. (Picture taken from Takayama et al. (2011)).

confident they felt about their answer. Results show that forethought was not significantly correlated to legibility, measured with the right prediction. But the participants were significantly more sure of their predictions. The method of our own experiments (Lichtenthäler et al., 2012; Lichtenthäler et al., 2012) regarding legible robot navigation is derived from the aforementioned method from Takayama et al. (2011) to measure legibility. In both experiments we wanted to investigate how legible different state-of the-art navigation methods are for a human observer. In the first experiment (Lichtenthäler et al., 2012) we recorded short simulator videos with a robot moving to one of three goals and a human crossing the robot's path (see Fig. 8) using four different navigation methods. As in Takayama et al. (2011) we divided the video into two parts. The first part ends before the human crosses the robot's path. We showed the participants the first part and asked them to predict the goal and to rate their confidence about their prediction. Afterwards we showed them the second part and asked them if the robot's actual behavior was as expected and how surprising it was. With these three questions we measured the legibility of the four different navigation methods. We found no significant association between the number of correct goal predictions, but the ratings for expectation and surprise differed significantly, which is in turn very similar to the results in (Takayama et

Figure 8. Experimental setup from our own experiment Lichtenthäler et al. (2012) where we measured the legibility of different navigation algorithms. The robot moves to one of the three tables and the human is crossing the robot's path. (Picture taken from Lichtenthäler et al. (2012)).

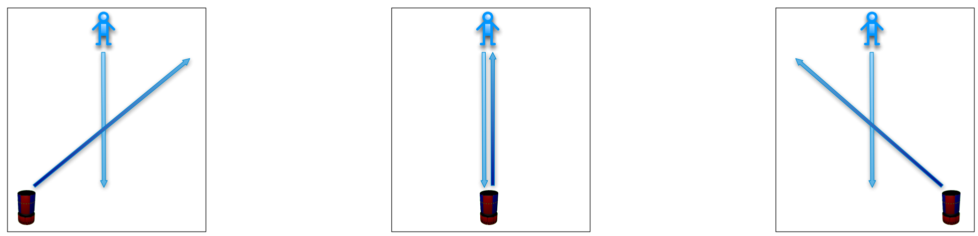


Figure 9. Experimental setup fom Lichtenthäler et al. (2012). The robot moves to one of the three tables and the human is crossing the robot's path. (Picture taken from Lichtenthäler et al.(2012)).

al., 2011). In our second experiment (Lichtenthäler et al., 2012) we used a similar method to investigate the correlation between legibility and perceived safety. Different from (Lichtenthäler et al., 2012) we used only two different navigation methods and prepared real world videos using a head mounted camera to provide a first-person perspective. As depicted in Fig. 9 the robot approached the human frontally and from each side. Similar to (Lichtenthäler et al., 2012; Takayama et al., 2011) we split up the videos at the point before the robot crosses the human's path. After the participants had seen the first part we asked them to predict the direction and velocity. After we showed them also the second part and asked them to rate whether the robot's behavior met their expectation. Additionally, we used the Godspeed V questionnaire (Bartneck et al., 2008) to measure perceived safety. Results show a significant correlation between perceived safety and legibility measured with correct predictions as well with the expectation ratings.

In (Lichtenthäler et al., 2011) we present different approaches of how legibility can be measured. Additionally to the formerly described use of questionnaires, we suggest to use psychophysiological measures. We suggest to measure prediction times, idle times, gaze behavior and skin conductance to assess how the observed robot behavior was perceived by humans. Prediction times were already used by (Gielniak & Thomaz, 2011; Dragan et al., 2013; Dragan & Srinivasa, 2013) as well as gaze behavior and skin conductance by (Dehais et al., 2011).

To conclude, within our review we found the following methods to measure legibility:

• Either show the participants robot motions/behavior or let them interact directly with the robot. Afterwards ask the participants to rate how legible the behavior was perceived (Dehais et al., 2011).

• Either show the participants robot motions/behavior or let them interact directly with the robot and use psychophysiological measures like skin conductance, gaze behavior (pupil size, fixations, saccades), to measure the arousal and anxiety. Thus, one gets an indirect measure for legibility. (Dehais et al., 2011; Lichtenthäler et al., 2011)

- Either show the participants robot motions/behavior or let them interact directly with the robot and ask to rate how surprising the behavior was perceived or if the behavior met the participants expectations.(Dragan et al., 2013; Lichtenthäler et al., 2012; Lichtenthäler et al., 2012)
- Show the participants robot motions/behavior and ask them to indicate immediately when they feel certain to predict the robot's intentions/goals and measure the time as indicator for legibility. Additionally, correctness and timing can be combined to one measure. (Gielniak & Thomaz, 2011; Dragan et al., 2013; Dragan & Srinivasa, 2013)
- Show the participants a video of robot motions/behavior and stop the video before the intention is clear and ask the participants to predict the robot's intentions. (Lichtenthäler et al., 2012; Takayama et al., 2011; Lichtenthäler et al., 2012; Basili, Huber, et al., 2012)
- In order to capture humans' expectations about robot motions one can ask participants to draw the expected trajectory (Dragan et al., 2013; Dragan & Srinivasa, 2013)

Furthermore, legibility was used as independent variable in order to investigate how legibility influences other factors (Eyssel et al., 2011; Bortot et al., 2013). Another indirect measuring method is to measure correlated factors of legibility. We present our findings regarding correlations of legibility in section .

Methods to Achieve Legible Robot Behavior

The question we want to answer in the following is how we can generate legible robot behavior. First of all we will elaborate the proposed assumptions and approaches on how to generate legible robot behavior. Later on we describe briefly the proposed methods.

Assumptions and Approaches. One obvious assumption regarding legible robot behavior is that **human-like** behavior would be perceived as legible (Beetz et al., 2010; Kruse et al., 2012; Guzzi et al., 2013), because human behavior is well-known for humans. Therefore, the development of methods imitating human motions is very common in the HRI community.

Furthermore, Beetz et al. (2010) claimed that a **stereotypical motion** is predictable, and thus legible. This assumption is supported by results from Bortot et al. (2013). In (Nehaniv et al., 2005) the authors claim that the use of **complementary motions** made by the robot could achieve legibility (e.g., during a hand-over arm motion looking to the object). Therefore, using their proposed gesture classification can improve the legibility of the robot. Furthermore, Sisbot and Alami (2012) integrated complementary gestures in order to make the motion more intend expressive. Moreover, Takayama et al. (2011) claims that the **use of animation principles** makes the robot behavior more legible. They implemented additional gestures in order to let the robot show forethought and the results of their conducted study supported their assumption. The "complementary gesture" assumption is also supported by results from Basili, Huber, et al. (2012). They could show that gaze behavior increases the ability to predict where someone is heading to.

Another assumption is to **take into account social constraints, human preferences and abilities** (Kirsch et al., 2010; Alami et al., 2006). Following this Kirsch et al. (2009, 2010) proposed an approach to achieve legible task execution behavior. They suggest to learn human preferences and abilities in order to integrate this knowledge into a high level task planner.

Visibility is not only a prerequisite for legibility, because a human is not able to anticipate anything from a hidden motion, it is also a very important factor for generating legible motions.

Sisbot et al. (2008) claims that *" a first step is to make the robot motion legible, is to make the handling position as visible as possible."*. Dehais et al. (2011) shares this view. This assumption is implemented in the Human Aware Motion Planner (Mainprice et al., 2011; Sisbot & Alami, 2012; Sisbot, Marin, & Alami, 2007; Sisbot et al., 2010) as well as in the Human Aware Navigation Planner (Sisbot, Marin-Urias, et al., 2007; Sisbot et al., 2005). The visibility assumption is based on results from Dautenhahn et al. (2006).

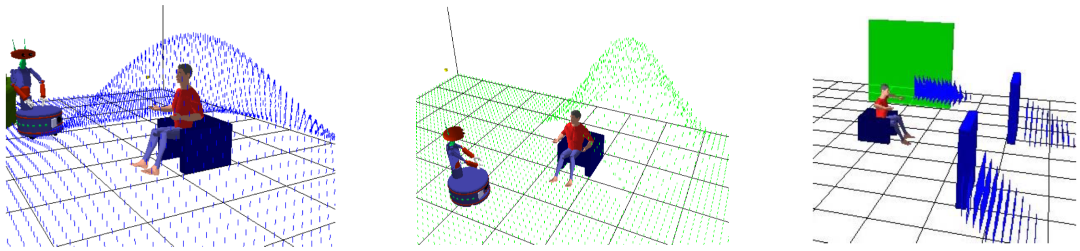
To conclude, in order to generate legible robot behavior, the following assumptions were proposed in the reviewed articles:

- model human-like behavior (Beetz et al., 2010; Kruse et al., 2012; Guzzi et al., 2013)
- generate stereotypical motions (Beetz et al., 2010; Bortot et al., 2013)
- add complementary motions (gestures) in order to clarify intentions (e.g. gaze, pointing, use animation principles) (Nehaniv et al., 2005; Sisbot & Alami, 2012; Basili, Huber, et al., 2012; Takayama et al., 2011)
- take into account social constraints, human abilities, and preferences (Kirsch et al., 2010, 2009; Alami et al., 2006)
- robot motion must be as visible as possible (Dehais et al., 2011; Sisbot et al., 2008).

Methods. In the following we briefly present the proposed methods to generate legible robot behavior. We will only describe the idea of the methods, for detailed descriptions we refer to the respective publications. In the literature at hand 18 articles are proposing methods to generate legible robot behavior like legible robot high-level plans (Alami et al., 2005, 2006; Kirsch et al., 2009), legible navigation (Sisbot et al., 2005; Sisbot, Marin-Urias, et al., 2007; Kruse et al., 2010, 2012; Guzzi et al., 2013), legible arm motions (Beetz et al., 2010; Dragan et al., 2013; Dragan & Srinivasa, 2013), legible hand-over motions (Sisbot & Alami, 2012; Sisbot et al., 2010, 2008; Mainprice et al., 2011, 2010; Sisbot, Marin, & Alami, 2007), or present methods to maximize the legibility of a gesture (Gielniak & Thomaz, 2011).

Legible robot task planning Human preferences and social constraints are considered in the Human Aware Task Planning method (HATP) proposed by Alami et al. (2005, 2006) and Alili, Warnier, Ali, and Alami (2009). They assume that taking into account human preferences and social constraints leads to legible plans. The HATP planning process is an extension of the SHOP2 planner (Nau et al., 2003), which permits to specify cost functions. In order to select the preferred behavior they used cost functions denoting the difficulty and pleasure an agent has in action realization, undesirable states, as well as undesirable action sequences, and representing social or cultural constraints. Kirsch et al. (2009) suggest to use learning methods in order to acquire knowledge about human preferences in order to integrate this knowledge into the planning process. In (Kirsch et al., 2009) they recommend to use the Robot Learning Language (RoLL) (Kirsch, 2008) for learning and updating human preference models.

Legible robot navigation In order to consider social constraints like safety, comfort and **visibility** for navigation path planning Sisbot et al. (2005); Sisbot, Marin-Urias, et al. (2007) model these constraints as cost functions (see Fig. 10) and use a classical A* path planning algorithm to compute legible paths. Kruse et al. (2010) propose a modification of the aforementioned HANP in order to achieve cooperative behavior that is more suitable for moving humans. They relaxed the safety cost function and shifted the safety constraint to the plan execution level to exploit the fact



(a) Safety cost function - as farther the robot is from the human the safer he interaction is - high costs for low distances

(b) Visibility cost function - based on the human field of view, high costs for invisible regions

(c) Visibility cost function representing hidden zones - high costs for regions covered by obstacles

Figure 10. Visualisation of the cost functions used by Sisbot et al. (2005) to model social constraints like safety and visibility in order to generate legible navigation paths or hand-over motions. (Picture taken from Sisbot et al. (2005)).

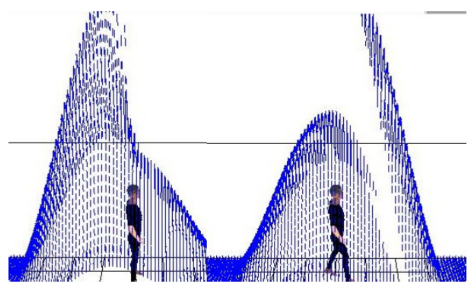


Figure 11. Visualisation of the cost functions used by Kruse et al. (2010) to model moving humans for robot path planning. As you can see in the right picture (moving) the costs in front of the human are higher to avoid moving in the humans way. (Picture taken from Kruse et al. (2010))

that the human might make room for the robot. Furthermore, they add a predictive cost function for moving humans to consider the future path of the human (see Fig.). Navigation methods imitating human behavior were implemented by Kruse et al. (2012) and Guzzi et al. (2013). Based on results of a human-human path crossing experiment Kruse et al. (2012) added a context-dependent cost model to their aforementioned extension of HANP in order to imitate the human behavior of moving straight forward and decreasing the velocity. Another human-inspired approach was presented by Guzzi et al. (2013). Contrary to Kruse et al. (2012), who are considering a one to one path crossing situation, the navigation algorithm implemented by Guzzi et al. (2013) imitates human pedestrian behavior in crowded multi-agent scenarios. The proactive method attempts to avoid potential collisions by using two simple heuristic rules to determine first the optimal direction towards the goal taking into account obstacles and other moving agents and second to determine a save and smooth velocity adjustment.

Legible arm motions Beetz et al. (2010) use Dynamic Movement Primitives to learn human reaching trajectories from a motion capturing dataset. These motion primitives were used to generate human like trajectories for a robot arm. A different approach was presented by Dragan et al. (2013); Dragan and Srinivasa (2013). They model the observers expectations as a cost function C in order to find the optimal trajectory. Due to their definition of a legible trajectory and the assumption that a goal is more likely when the movement is towards it and away from the other goal, the cost function C computes the probability for a goal given a trajectory. Thus, they compute the optimal trajectory in terms of the ability to predict the goal as soon as possible. Predictability is modeled as an efficient trajectory with a cost function C determined by the path length.

Legible hand-over motions In order to generate legible hand-over motions Sisbot and Alami (2012) developed the Human-Aware-Manipulation-Planner (HAMP) based on the Human Aware Navigation Planner HANP using the same cost function approach (Sisbot, Marin, & Alami, 2007; Sisbot & Alami, 2012; Sisbot et al., 2010, 2008). The planner consists of three stages. First, the planner determines the optimal spatial coordinates for the object exchange point that is safe, visible, and comfortable to reach for the human. To achieve this, they search for a point with the lowest costs considering safety (see Fig. 10 (a)) and visibility (see Fig. 10 (b)) cost functions, which had already been used in the HANP. Furthermore, they use an arm comfort cost function, which determines costs representing how comfortable it is for a human arm to reach a point, based on a kinematic model. The second step is to find the optimal path for the object from the initial position to the object exchange point. Equally to the method used for HANP, the motion planner calculates the optimal path for the object transfer using the A* algorithm and the safety and visibility cost functions (see Fig. 10). Third, the robot motion has to be calculated considering the object path. To this end, they use a generalized inverse kinematics algorithm (Sisbot, Marin, & Alami, 2007) and a Soft Motion Trajectory Planner, which transforms a path into a trajectory with bounded jerk and acceleration, thus generating a smooth robot motion that is aimed to be more natural and human friendly. (Sisbot et al., 2010). Furthermore, Sisbot et al. (2008, 2010) added additional camera and head motions in order to increase legibility by expressing intention using gaze behavior.The robot moves its head and cameras to look at the object during the handover task. Mainprice et al. (2010, 2011) enhanced the existing HAMP by using a different path planning algorithm.

Enhance legibility Takayama et al. (2011) increased the legibility of a given behavior, like opening the door, by adding an additional gesture showing forethought to the original behavior. Their approach is to use animation principles from the Disney Studio (Thomas & Johnston, 1995). However, the motions are animated using a animation software suite and not implemented (see Fig. 7). Another approach to increase legibility is the algorithm presented by Gielniak and Thomaz (2011) to enhance the legibility of a given gesture. They analyzed a given gesture like a *"I don't know"* gesture in order to find the body configuration representing a *symbol*, which is the most expressive part of the gesture (see Fig. 4). Afterwards, they created a motion from the original gesture motion in which the *symbol* occurs as soon as possible.

Factors Correlated to Legibility

In the last section of our literature review we present the results of our research regarding the question, which other HRI factors are correlated with legibility. In seven publications correlations are assumed and in seven scientifically evaluated.

The factors safety and comfort seem very likely to be correlated with legibility, because an unforeseeable and sudden movement of the robot could cause a collision, let the human feel unsafe and also very uncomfortable. Sisbot and Alami (2012) wrote in context of the Human Aware Motion Planner that *"even if the robot position and objects position will be good, an unclear motion that does not reflect the robots intention (= not legible) can* ***surprise*** *human and cause* ***discomfort****"*. Furthermore, Sisbot et al. (2010) stated that *"a legible interaction adds to safety"*. Also Kirsch et al. (2010) claimed that *"legibility is a prerequisite to establish human* ***comfort*** *and* ***perceived safety****, because if the intention of the robot is understandable, its actions can be expected and are not felt as a threat."*. The aforementioned statements are in line with Kruse et al. (2010). The influence of legibility on safety and comfort were investigated in an experiment conducted by Dehais et al. (2011). Although the authors did not calculate a correlation coefficient, their presented results let us presume a correlation between legibility, safety and physical comfort (see Table 1).

Table 1: Results of the evaluation of the three tested hand-over motions regarding legibility, safety and comfort using a 9-point visual analog scale (1 for very low, 9 for very high. The values were obtained by Dehais et al. (2011).

Subjective variables	Motion-1	Motion-2	Motion -3
Legibility	7.33 (± 1.18)	4.00 (± 0.72)	3.58(± 0.54)
Safety	7.00 (± 0.39)	2.25 (± 1.05)	4.66 (± 0.57)
Comfort	6.33 (± 0.43)	2.83 (± 0.92)	1.83 (± 1.03)

Similar to the investigations of Dehais et al. (2011) we also evaluated the legibility, safety and comfort of different algorithms (Lichtenthäler et al., 2012). The results let us also presume a correlation between legibility, safety, and comfort[7]. In our second experiment, where we further investigated the influence of legibility on perceived safety (Lichtenthäler et al., 2012) we found a significant correlation between legibility and safety.

Another factor influenced by legibility is the **efficiency** of the interaction. Guzzi et al. (2013) explained this correlation with a vivid example from robot navigation: *"If navigation algorithms generate unpredictable trajectories, humans have to frequently change their local plans to move around the robots, ultimately resulting in less efficient navigation for both groups"*. Also Kruse et al. (2010, 2012) assumed a correlation between legibility and the efficiency of the interaction. Bortot et al. (2013) measured the human performance in a cooperative task and their results confirmed the assumption.

Takayama et al. (2011) investigated the factors appealing, intelligence, competence, safety, approachable and confident, but their results do not show any clear correlation. The effect of legibility on anthropomorphism was studied by Eyssel et al. (2011). However, they found no significant correlation between the factors. In (Lichtenthäler et al., 2011) we assume that the perceived value of a robot is influenced by the legibility of the robot behavior.

One insight of an experiment conducted by Dragan et al. (2013) is that the factors legibility and predictability of goal directed arm motions are inversely correlated.

We conclude from our literature review that the following factors are correlated with legibility:

[7] A subsequent data analysis on the dataset revealed a significant correlation between legibility (measured by the level of surprise) and safety ($r = -0.323^{**}$),as well as legibility and comfort ($r = -0.395^{**}$). ($^{**}: p < 0.01$)

- safety (assumed in (Kirsch et al., 2010; Sisbot et al., 2010), experimental investigations in (Lichtenthäler et al., 2012; Dehais et al., 2011))
- comfort (assumed in (Sisbot & Alami, 2012; Kirsch et al., 2010), experimental investigations in (Dehais et al., 2011; Lichtenthäler et al., 2012))
- surprise (assumed in (Sisbot & Alami, 2012; Mainprice et al., 2011), experimental investigations in (Lichtenthäler et al., 2012; Lichtenthäler et al., 2012))
- efficiency (assumed in (Guzzi et al., 2013; Kruse et al., 2010, 2012), experimental investigations in (Bortot et al., 2013))
- perceived value (assumed in (Lichtenthäler et al., 2011; Lichtenthäler et al., 2012))

Discussion

Within the review at hand we summarized the findings, assumptions and methods other researchers made and developed regarding legible robot behavior. First of all, we conclude that we can define a robot motion as legible if a human observer/interactor is able to **(1) understand the robot's intentions** - meaning that a human can figure out what the robot is actually doing and is able to predict the trajectory as well as the goal of a movement, or the meaning of a gesture - **(2) the robot behavior meets expectations**. In order to achieve legible robot behavior we found the assumptions in the reviewed articles, that a motion is legible when it is human-like, stereotypical, efficient, as visible as possible, considers social constraints and human preferences. Furthermore, we fund the suggestion that and one could add complementary motions to clarify the robots' intentions. We presented several ways to measure legibility (see Section) e.g. by using self-reports or by measuring the time one needs to predict the intention of a robot motion. Furthermore, we elaborated methods to implement legible motions (see Section) and summarized the factors that are correlated with legibility such as safety, comfort, surprise, efficiency, and the perceived value of a robot.

One very interesting thing we found is that almost all reviewed articles are holding a similar view on legibility and the results are in line with each other, except the work from Dragan et al. (2013); Dragan and Srinivasa (2013). In their experiment they had a very interesting result regarding the factors legibility and predictability namely that *predictability and legibility are fundamentally different and often contradictory properties of motion"* (Dragan et al., 2013). As opposed to the other authors they defined and measured legibility as the ability to infer the goal as soon as possible and predictability as the ability to infer the trajectory of a robot arm moving towards one of two goals. In the other articles of the review at hand these two aspects are not differentiated. Furthermore, no other factors like safety, efficiency or comfort were investigated within their experiments. Considering the results from Bortot et al. (2013) we can conclude that the straight and according to Dragan et al. (2013) predictable motion is more efficient than the legible motion. It would be very interesting to investigate the safety and comfort of these two aspects of a motion.

Our overview of measurement instruments to determine the legibility of robot behavior (see Section) adds to the field of HRI metrics (Bartneck et al., 2008; Bethel, Salomon, Murphy, & Burke, 2007; Heerink et al., 2009) and extended the common HRI measurements by the factor legibility. Nevertheless, much work is still to be done in order to develop further methods to measure legibility. Furthermore, the fact that several authors present concrete methods to achieve legible robot behavior and our findings regarding correlated factors support our former assumption that legibility is one important factor of robot acceptance (Heerink et al., 2009) and should line up with the HRI key concepts (Bartneck et al., 2008).

Within the review at hand several open questions came up, which in our opinion should be investigated in the future. As aforementioned the results of Dragan et al. (2013) especially in comparison to the other presented findings motivate several open questions like ”Are the results transferable to navigation?” or ”Which HRI factors are influenced and is there also a difference for the two Dragan factors legibility and predictability?”. Further investigations regarding the two factors goal predictability and trajectory predictability of a motion will be very interesting.

Moreover, correlated factors of legibility should be further investigated. Not only the aforementioned factors like safety, comfort and efficiency need further considerations, there is also a need to look at other HRI factors like perceived intelligence, likeability (see (Bartneck et al., 2008)) or indicators of robot acceptance like intention to use, usefulness or enjoyment (see (Heerink et al., 2009)). Another interesting question is: How can gestures increase legibility? and furthermore: Which kind of gestures are useful? Here we suggest to develop a gesture toolbox to increase the legibility of a given behavior.

Finally, we can conclude from the review at hand that legibility is an important factor for cooperative human-robot interaction that needs to be further investigated and has to be taken into account when developing robot control methods.

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