

Review

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Review

Psychophysics of Social Cyber-Physical System Acceptance

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Abstract: A review of literature, supporting the view on the psychophysical origins of some acceptance effects of cyber-physical systems (CPSs), is presented and discussed in the paper. Psychological effects like the *reactance* to a robot or the *uncanny valley phenomenon* suggest that CPSs are perceived as a special type of 'being', a phylogenetically emergent category, or a novel ontology in a philosophical sense, culturally developing as a function of the social brain. Justification of this view is provided by the psychophysically-relevant human responses to technologically and socially ambiguous stimuli on the one hand, and the probabilistic independence of the proposed ontology to similar ontologies, subjectively experienced by the human, on the other. The results of the presented in the paper analysis demonstrate the feasibility of the proposed hypothesis of ontological 'near independence' of the distribution of the probabilistic psychophysical processes in response to the cyber-physical stimulus as a socially evolving phenomenon.

Keywords: cyber-physical systems; robot acceptance; psychophysics; psychological reactance; categorical perception; uncanny valley effect; probability distribution; accessibility

1. Introduction

The introduction of cyber-physical systems (CPSs) has become ubiquitous, raising issues of adequate design and reliable interdependencies between their different components (technical and social), being in itself of large societal impact [1,2]. Some of these CPSs are especially designed with interfaces, which are able to convey social communication (such as chat bots in various applications), education (e.g. LEGO [3] or MIRO [4] robots), as well as perform psycho-social or pedagogical rehabilitation roles [5–8].

Numerous factors of user *acceptance* of such socially functioning CPSs, including cognitive and neuro-cognitive mechanisms, have been intensively studied recently [9]. Psychological effects like *reactance* to a robot [10] or the *uncanny valley phenomenon* [11] suggest that CPSs are perceived as a special type of 'being', sharing features of a non-living entity/machine with a living (human or animal) being. Several theoretical accounts of the emergent 'human-robot interaction realm' have been forwarded in the recent century in support of the following view: *it is not straightforward* to predict conditions (extrinsic or intrinsic) for smooth human-robot interaction *by simply* following the already available knowledge of human-human interactions. The reason is that technology in general, and robots/CPSs in particular, present a novel *perceptual, categorical* and *interactive* stimulus for the cognitive system of the user. The psychophysical effects, caused by such a novel stimulus, need to be further explored (theoretically and experimentally) to establish the relevant cognitive and socio-cognitive laws, guiding user behavior in the present-day complex technologically-mediated social environment.

Some important accounts of robot *acceptance* by the human are formulated in recent theories, such as: the theory of violation of predictive coding [12–14], realism inconsistency theory [15], distortion of categorical perception theory [16], robot mediation in social control theory [18], and several others. An interesting question is whether the subjective response to the robot is *independent*

(in probabilistic terms), from the response to a human, to any non-human, or to both. A positive answer to this question may signify the emergence and validity of a novel subjective socio-cultural *category* of everyday agents, commonly called *social robots*, or social CPSs [19,20].

The proposed in the present paper theoretical account of social CPS *acceptance* follows Moore's theory of perceptual distortion at category boundaries [16], which is most likely to occur in the areas of overlap of the distributions of the subjective effects in the mental representation, produced by the encounters of the cognitive system with a *human*, or a *non-human* entity (being probabilistically independent events). We assume probabilistic independence not only between the distributions of the psychological effects, caused by the categories 'human – non-human', but by the categories 'human – robot', and 'robot – non-human' (Figure 1) As it will be discussed later in the paper, the actual relation will be assumed similar to the so called 'near independence' in terms of the probabilistic theory of Tulving and Wiseman [21], which is the result of the actual *distortion* of the normal distribution of the psychological effects towards somewhat bigger feature overlap, resulting, as a consequence, in 'perceptual confusion', possibly causing a negative reaction towards the robot in cases of close perceptual resemblance of the robot to a human/living being.

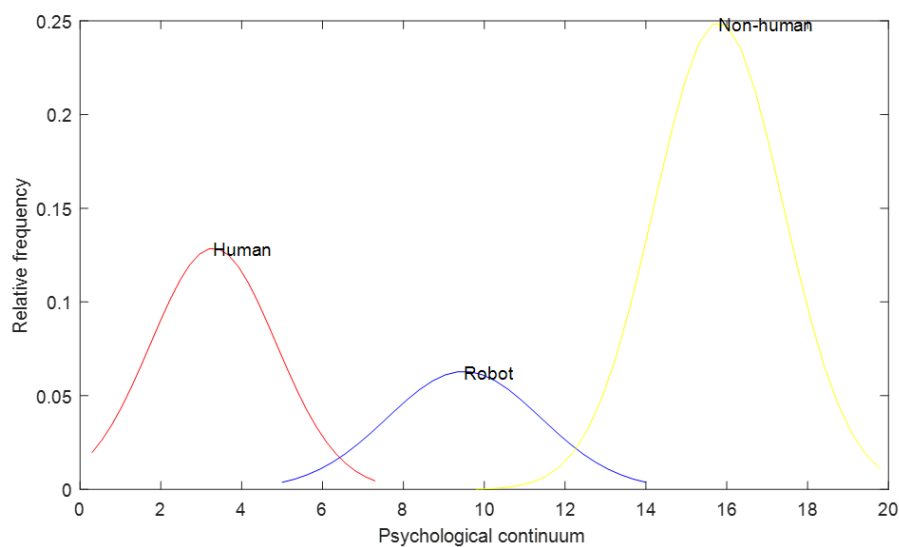


Figure 1. Possible relations of probabilistic 'near independence' between the categories of the human, robot and the non-human.

A recent systematic review of human *acceptance* of social robots provides evidence of the human having *generally positive attitude* towards social robots, hypothesizing the following intriguing possibility - to "acknowledge the qualities that mark social robots as not just another technological development but perhaps as an *entire new social group*¹ with its own complexity" [22] - citing the earlier work of one of the authors [23]. In the latter work a new ontological category is being proposed – that of the robots as technological tools, which are perceived as *more than* just machines, i.e. as entities, possessing some distinctive features of 'agenthood' [24]. The present paper considers the level of the *psychophysical* response to the newly emergent complex stimulus – the CPS or the robot – with its *instantly* presented perceptual features of physical, technical, technological, bio-physical and social appearance.

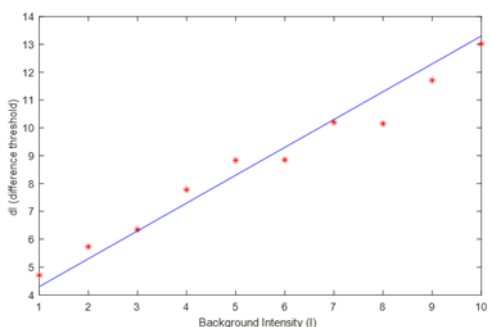
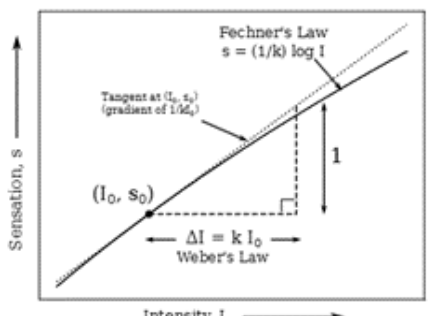
Psychophysics is traditionally viewed as a science, concerned with projecting a mental topology onto the physical reality, obeying certain mathematical laws of transformation. Examples of such laws are: Weber's law of detection of just noticeable differences (JNDs) [25], Fechner's Law of intensity discrimination [26], Steven's power law of transformation of the stimulus intensity into the intensity of the sensation [27] and Tulving's theory of trace 'near independence' when memorizing a stimulus [21]. It was convincingly demonstrated in recent works that the manifestation of these cognitive effects, being the fundament of psychophysics, can be meaningfully accounted for in

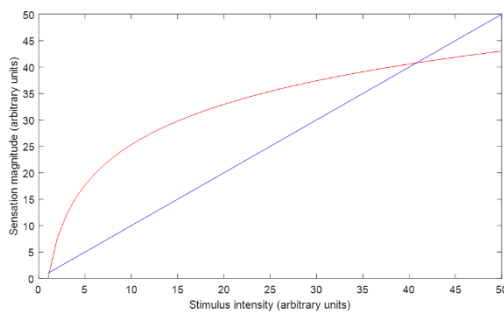
¹ Italics is ours.

probabilistic terms and models (as are higher level cognitive representations) [28,29]. The latter assume that the *entry point* of any sensation, coming from the external environment, produces not a single reaction/response, but a *distribution of sensory effects* translating the physical intensity via electro-chemical reaction into a set of discrete electrical reactions of the neuron to forward the signal distribution towards the generation of complex *psychophysical* and psychological phenomena [29].

A bridging theory between sensory psychophysics and higher psychological levels of decision making can be considered the theory of Thurstone [30,31], who proposed the law of comparative judgement, being largely compatible with the other psychophysics laws from a probabilistic perspective, as demonstrated in [32] (Table 1).

Table 1. Basic psychophysics laws and their psychological relevance to the issue of human-robot interaction from an *acceptance* perspective.

Name	Definition	Relevance to HRI
Weber's law	<p>"If X is a stimulus magnitude and X + ΔX is the next greater magnitude that can just be distinguished from X, then Weber's law states that ΔX bears a constant proportion to X data" (33, p. 177).</p>  <p>Adapted from [33].</p>	<p>The JND depends on the psychological effect of the background stimuli, meaning that sometimes a small incremental change of a stimulus can lead to a bigger response in comparison to the same change of a larger stimulus (i.e. noise). On an abstract decision making level small JNDs may invoke large responses depending on the contexts, i.e. larger to perceptually confusing, than to unambiguous, human or robot parts (faces, hands, etc.)</p>
Fechner's law	<p>"... if ΔX bears a constant proportion to X, so also does X + ΔX, and $\ln(X + DX) - \ln X = \text{constant}$" (20, p=177). Therefore, the sensation is a logarithmic function of the stimulus intensity: $S = \ln X + \text{constant}$.</p>  <p>Reproduced from [34] under Creative Commons Attribution (CC BY) license.</p>	<p>Fechner's law accounts best for the (almost) linear part of any measurable in the lab "stimulus-response" dependency of <i>midrange</i> intensity. On an abstract decision making level it supports the assumption that any cognitive system, as function of the underlying neurological brain processing, is a measuring <i>device</i> best adapted to an Euclidean topology of representation of the external environment [28].</p>
Steven's law	<p>"... sensation was correctly reflected in magnitude estimation and was related to stimulus magnitude by a power law, $S = aX^{\beta}$... not a log law data" [35], (p.178).</p>	<p>Steven's law assumes that the human cognitive system is capable of mapping adequately the <i>ratios</i> of the responses to the <i>ratios</i> of the stimulus intensities, i.e. of higher level assessment of mathematical dependencies, existing in the environment. Therefore, it</p>

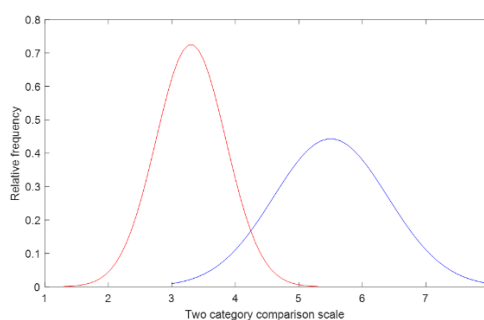


Adapted from [35].

translates beyond the (physical/electro-chemical) properties of the sensor to the complex analyser abilities of the integrative function of the brain. It also states that, apart from the linear part of the power function, small increments of intensity result in an exponentially high increment of the response (i.e. pain, where the power degree is > 1). With strong light, for example, the power degree is < 1 (as in the figure to the left).

“the distribution of attitude of a group (of people*) on a specified issue may be represented in the form of a frequency distribution...limited to those aspects of attitudes for which one can compare individuals by the "more and less" type of judgment...The scale is so constructed that two opinions separated by a unit distance on the base line seem to differ as much in the attitude variable involved as any other two opinions on the scale which are also separated by a unit distance [32] (p.529).

Thurstone law



Adapted from [32].

Thurstone demonstrated that Weber's and Fechner's laws are independent from each other [27]. He proposed a method of indirect scaling, allowing to devise an *interval* scale of seemingly non-measurable qualities such as social attitudes. This method is therefore appropriate to formally represent in quantitative ways the distances between characteristics of radically different complex items like robots or people. Moreover, it reflects the ability of the brain to perform processing over complex multidimensional probabilistic representations - physical and social.

Tulving's law of recognition failure

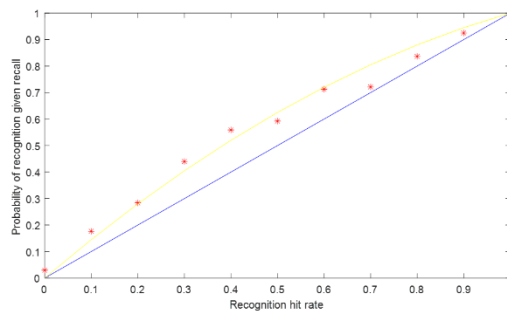
Tulving's law of recognition failure postulates a slight distortion of the independence assumption of 2 cognitive processes – recognition R_n and recall R_c operating over the mental representation of one and the same stimulus [21]. The probability of jointly recognizing and recalling a stimulus is expected to slightly violate the independence assumption, i.e.

It is well known that when the conditional probability of an event $P(R_n | R_c)$ in respect to another event $P(R_c)$ equals its probability of occurrence of $P(R_n)$, the two processes are independent [36]. In the theory of Tulving and Wiseman [21], this independence relation is slightly violated by a fraction δ , where $\delta = c[1 - P(R_n)]$, c is a coefficient in the range (0, 1].

Tulving's theory of 'trace independence' when memorizing a stimulus demonstrates that what is learnt depends of the surrounding context of the learning situation, on the one hand, and the multiple,

$$P(Rn|Rc) = P(Rn)P(Rc) + \delta, \text{ or}$$

$$P(Rn|Rc)/P(Rc) = PRn + \delta.$$



A hypothetical plot of the above function.

*Added by us.

almost *independent* memory traces, created during learning, on the other [21]. This may apply to memorizing complex stimuli with sophisticated behavior, like robots, as well.

These psychophysical ‘laws’ deal with human *assessment* as a function of some cognitive measurement *device*, performing on the abstract representation of the external stimulus in the human mental representation’s space, which may, or may not, be entirely *congruent* [37] to the underlying brain processing of the same stimulus, thereby creating a meaningful and truthful picture of the objective world. Such a possibility is being supported by studies, mapping linear to nonlinear transformations of processes in the psychophysical effects onto neuronal activities in fMRI studies like in [38].

On the one hand, a CPS, or a robot, can be a physical entity with little, or none, biologically inspired features, but on the other – it can resemble biological tissue – and even deeper, psychological levels of performance of various creatures – real or imaginary. In such complex cases, the emotional/affective component in perception is inseparable from the cognitive component, as revealed by the so called Thatcher illusion [39]. The illusion consists of strong emotional response to distorted faces when presented in an upright orientation, but not when inverted. It is suggested by such illusions that the psychophysics of user perception of complex physical objects/entities/counterparts reflects the emotional component as well, not just for the *objective mental projection only* of the perceived stimulus. So, the psychological (cognitive and emotional) processing, when we ask people how they perceive a robot is, without any doubt, *deep, elaborate, complex and emotionally charged*.

2. Classical Psychophysical Assumptions Relevant to CPS Acceptance as a Psychological Reality

Robot acceptance has been interpreted as a psychological reality in [40]. Three abstract processes are outlined in the interaction with service robots: functional, informational and relational. The first two characterize the interaction with any technology, whereas the third one deals with specific *relations* to be established with the new ‘social’ entity – like *benevolence, satisfaction* and *understanding*. The law of comparative judgement of Thurstone has been successfully used in cases when interval scales of subjective opinions on similar abstract attributes are needed for different purposes, including for understanding, for example, of the psychological and neural mechanisms “for accepting and rejecting artificial social partners in the Uncanny Valley” (40, p. 339). The underlying psychological processes are rather *implicit*, than explicit, and can be modelled in a psychophysical framework, based on the descriptions, given in Table 1. It presents the above mentioned psychophysics laws and their psychological relevance to the issue of human-robot interaction (HRI) from a novel *acceptance* perspective, which we call PRAM (Psychophysics of Robot Acceptance Model).

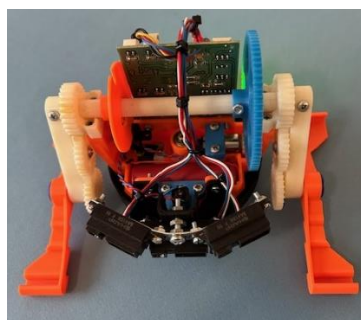
PRAM asserts that the classical and modern psychophysical assumptions describe the regularities of the *internal* processing of the complex environment, in which the human exist – physical, technological and social - on different conceptual levels of mental abstraction, reflecting the complexities of the attributes of the objects in the world. Justification of this view can be found in [29], referring to the classics of psychophysics from a modern perspective: “Fechner seemed to have

a clear notion of what had to be done to translate the study of outer psychophysics to the study of inner psychophysics (Fechner 1860, p. 56): “Quantitative dependence of sensation on the [outer] stimulus can eventually be translated into dependence on the [neural activity] that directly underlies sensation—in short, the psychophysical processes—and the measurement of sensation will be changed to one depending on the strength of these processes.” When people coexists with a robot in various social situations at work, home, hospital, etc. – the attributes of the robot are being processed from many facets – crucially important to their survival, including some of the presented above psychophysical laws of stimulus discrimination.

3. A View on the Psychophysical Distance between the Robot and Human Agent Stimuli

Returning to the theory of Moore [16], described in the introduction, it plots the probability of naming a stimulus a ‘robot’ as non-independent from perceiving the stimulus as a representative of the ‘non-human category’, which has a larger standard deviation (since numerous items can be perceived as non-human in type). The probability of responding by ‘human’ to a human stimulus is independent from the probability of responding ‘robot’ to a ‘non-human’ stimulus, according to [16]. An alternative view, as proposed in the present paper, would be to assume the ‘robot’ category independent or ‘nearly’ (in Tulving’s terms [21]) independent from *both* the human and ‘non-human’ categories. If the foreseen ‘near independence’ is observed in experimental studies, this would provide yet another explanation of the nature of human *reactance* to humanoid robots, or the emergence of the *uncanny valley* phenomenon as a perceptual mismatch of subjectively incompatible, but overlapping in some features, categories, existing as new *ontologies* of agents emerging in the course of the social development in the recent centuries. This will support the view, proposed in the present paper, of user reaction to a robot as a socially evolving phenomenon and its *acceptance* by the human as a function of the evolution of the social brain.

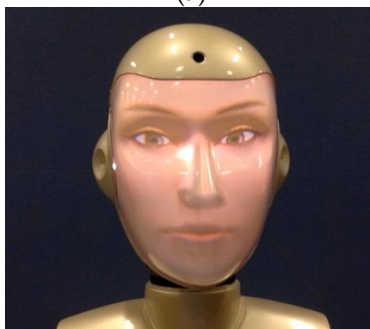
As an example, illustrating the above statement, consider Figures 2 and 3. Figure 2 presents photos of 4 agents, which we have used in our previous research on user acceptance of robots/CPSs in various roles, such as a toy - the walking robot BigFoot [41], a), a zoology teacher - the humanoid robot NAO [42], b), and counseling assistant – the android type of robot SociBot, [43], which we have called Alice c). The user reaction to videos of Alice and NAO was compared to the reaction to the video of a human actress (by the name of Violina), d), along dimensions such as *sociability* or *trust*, in [6].



(a)



(b)



(c)



(d)

Figure 2. Previously used agents in studies on user acceptance of robots: (a) A walking robot BigFoot; (b) The humanoid robot NAO; (c) The android type of robot SociBot; (d) A volunteer actress.

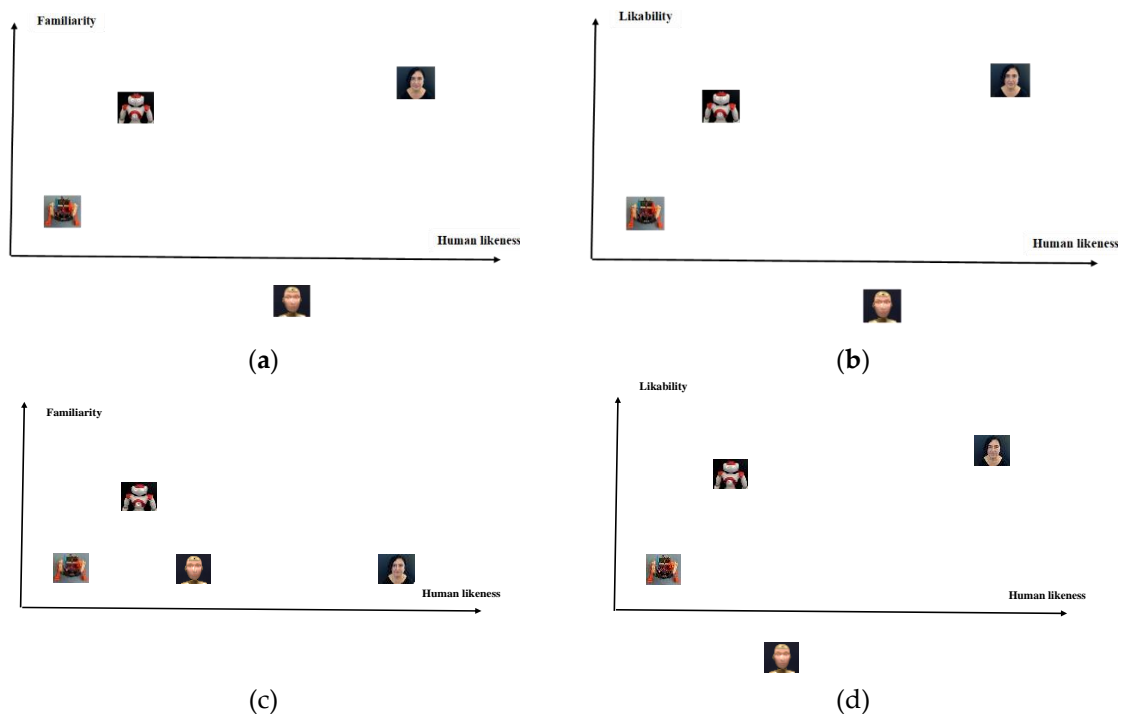


Figure 3. Plots of the expected uncanny valley function in 4 different cases: (a) Plot of *familiarity* as a function of *human likeness* in the classical case; (b) Plot of *likeability* as a function of *human likeness* in the classical case; (c) Plot of *familiarity* as a function of human likeness in the proposed PRAM case; (d) Plot of *likeability* as a function of *human likeness* in the proposed PRAM case.

The main outcome from the study was the *lack* of a statistical effect of type of face on the feature assessment process, which supported the idea that humanoid robots can perform tasks and roles, typical for the human, even exhibit professional skills [6]. Interestingly, viewers assess differently the positive and negative features (main effect of factor feature type), of the presented faces – human, android or robotic (machine-looking). They tend to be cautious in negatively evaluating neutral faces, and are inclined to see positive features in these faces to a larger extent. One possibility is that the used stimuli – the robots – are selected to avoid possible repulsive features by design. This inevitably would change the form of the Mori's function. At the same time the general tendency, in terms of the hypothetical mental distance on the feature dimensions, would be preserved.

Figure 3 plots the hypothetical *uncanny valley effect*, expected at the encounter of each of the above agents, according to the proposed theoretical account of robot acceptance by the human (PRAM). The *reactance* effect is assumed identical with the *uncanny valley* effect in terms of its *valence*, but different as an *intensity* of reaction – psychological, in the first case (reactance), and visceral – in the second (uncanny valley) [6].

The classical *uncanny valley function* depicts the functional relation between 2 dimensions – *human likeness* and *affinity* [11]. The horizontal axis x represents the *human likeness*, whereas the vertical axis y represents the *affinity* in Mori's terms. In more recent studies it was accepted to split the affinity attribute/feature into *familiarity* and *likeability*, since the original *affinity* feature is a complex attribute, which is easily understood in Japanese, but not possible to translate unambiguously in English. By being non-independent statistically, *familiarity* and *likeability* are used to complement or confirm the main assumptions on investigating various factors, which may produce the psychological effect of *uncanny valley* in cases of encounter of any one of the artificial agents [38]. Cases (a) and (b) of Figure 3 represent hypothetically the classical view of the *uncanny valley* effect, whereas cases (c) and (d) – the psychophysical view (PRAM), forwarder in the present paper.

Consider the probabilistic distributions of the subjective effects, plotted as a Mori's function along two dimensions. The unambiguous dimension is the x axis, called *human likeness*. The y axis can be familiarity, or likeability – so 2 cases of y as a function of x are possible – familiarity, depending on human likeness and likeability, depending on human likeness. The effect is a sudden drop of the y value as a function of high human likeness of an artificial agent, and sharp increase of the y function when a human is displayed instead.

The machine looking toy robot BigFoot is expected to be placed at the left origin of the *human likeness* dimension in all 4 cases of Figure 3. The robot is the least resembling a human, least *familiar* and, possibly, least *liked* one. The position of the humanoid robot NAO, popular for being designed as cute and likable by children, will possibly be approximately in the same position in all 4 cases, too – more *human-like* than BigFoot, *familiar* as being quite frequent, and *likeable* by design. The relative positions of the android and the human faces, however, differ, depending on the classical or the proposed PRAM cases. In the classical case the *uncanny valley* function would predict a drop below the zero line of the y axis with the increase of human like features of the artificial agent Alice. This drop below the y axis signifies the *affective* (negative emotional) reaction to the android, closely resembling perceptually a human agent. Alice is *unfamiliar* (a) and possibly not much *liked* because of this (b). In both cases the human face is the most *familiar* and *likeable* (though never seen before).

The proposed here account predicts probabilistic independence of the three categories – among the distributions of the psychophysical effects of the non-human agent (BigFoot), the robot agents (NAO and Alice), and the human (Violina). The crucial prediction is the similarity (or non-independence) effects of NAO and Violina. In case (c), only NAO is familiar, whereas BigFoot, Alice and Violina are never seen before and the familiarity effect will be similar for all of them. At the same time the *human likeness* is distinctly different in all 3 robotic cases. By applying the Thurstone's scaling procedure, it is possible to determine the exact position of each of the agents on the *human likeness* scale/dimension for each of the experimental conditions.

Considering case (d), it is not quite possible to predict which agent will be most liked. All faces have neutral expressions, and the classical condition of the expected repulsion by the artificial agent will not hold to the full extent. At the same time, by being dependent on the individual internal criterion (according to Moore [16]), and by applying the scaling method of Thurstone [30], it will become possible to design robotic scenarios, which are tailored to the preferences of the individual user of the robot *both* extrinsically (verbal report) and intrinsically (psychological/visceral reaction). Consequently, the proposed PRAM approach presents itself as an overall methodological framework, applicable for *accessibility* design of CPSs, intended to support better access to knowledge with the help of CPSs/robots also by users with special learning needs.

4. Conclusion

The presented in the paper review analysed the existing approaches to model the acceptance by the user of autonomously performing artificial agents/CPSs, often referred to as social robots for being able to interact meaningfully or usefully with a human user – in rehabilitation, school, counseling, or as service robots. Several psychophysical laws are systematised from the point of view of their relevance to model the psychological processes underlying user acceptance of these technologies within a novel theoretical framework called PRAM (Psychophysics of Robot Acceptance Model). It was applied for hypothesis generation for future experimental studies, which can provide useful design guidance of CPSs, which are acceptable and individualized to the sensor and learning needs of the users.

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