A Conceptual Model of Personal Space for Human-Aware Robot Activity Placement

Felix Lindner[1]

***Abstract*— This work proposes a conceptual model of personal space that can be used within symbolic knowledge-based robot architectures. The robot represents personal spaces in terms of affordance spaces attached to humans, i.e., portions of physical space that can be used for interactions. The model does not rely on numeric functions nor does it impose any restrictions upon the geometry of personal space. The approach is applied to human-aware robot activity placement planning: Given an activity type and a robot that is to perform an activity of this type, principles of personal space use determine the reasons pros and cons to place that particular activity at a particular affordance space. The symbolic representations of personal spaces enable robots to make choices and to communicate the reasons for their choices to humans.**

I. INTRODUCTION

Empirical studies give evidence that the spatial distances robots maintain during interactions with humans play an important role in how humans perceive and accept the interaction with a robot (e.g., [1], [2], [3]). Hence, the concept of personal space as described by the anthropologist Edward T. Hall [4] has inspired several approaches to modeling robot spatial behavior in human-robot interaction. Figure 1 shows a schematic picture of personal space and its regions according the model of Hall. Each human owns a personal space and each of its regions bears a social meaning.

The goal of this work is to take a knowledge-representation perspective on modeling personal space for social robotics. In this respect, it makes two conceptual contributions: First, the proposed model is formalized using logics and thus can be represented within symbolic knowledge bases and common sense ontologies. Unlike most existing models of personal space proposed in robotics, the model does not use numeric functions and imposes no restrictions upon the geometry of personal space. At the same time, it acknowledges that personal space is grounded in the possibilities for interactions provided by humans. Second, the model captures a dual use of personal space. On the one hand, models of personal space are used to control social robots' distances to humans they interact with (e.g., [2], [5], [6], [7]). On the other hand, personal space models ensure that mobile robots maintain appropriate distances to humans they do not interact with, for instance, while passing by (e.g., [8], [9], [10], [11]). As noted in [12], in passing-by situations, humans maintain shorter distances as compared to the distances predicted by personal space models that adhere to the model of Hall. Borrowing Goffman's [13] terminology, this relates to the distinction between focused and unfocused interactions. As will be demonstrated, both these phenomena can be represented within one single model of personal space.

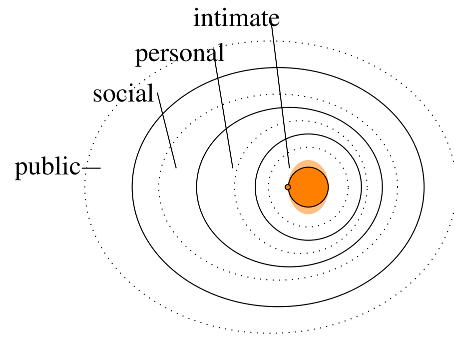


Fig. 1. Schematic depiction of personal space according to Edward T. Hall (see [4]). Personal space consists of an intimate region, a personal region, a social region, and a public Region. Each of these regions is internally structured into a close and a far region.

The paper is structured as follows: The next section briefly reviews models of personal space proposed in social robotics research. Section III proposes a new model of personal space based on affordance spaces [14]. Under this perspective, personal spaces are agglomerates of affordance spaces, which can be used to realize affordances provided by humans [15]. Section IV shows how the proposed model can be used to determine the socially most adequate placements for a social robot to interact with a human. A knowledge-based architecture that has been implemented and applied to several simulation case studies is discussed in Sect. V.

II. RELATED WORK

Existing models of personal space proposed in robotic literature can be grouped into geometric models and potential field models. Geometric models of personal space are composed of ellipses or semi-ellipses. Examples of this modeling approach can be found in [5], [10], [25], [24]. Geometric models of personal space have crisp boundaries. Therefore, they are well suited to represent sharp transitions between different regions of personal space [5], [10] or to represent personal spaces in nearness histograms for local navigation [25], [24]. Except from [5], these models are applied solely to the task of avoiding humans.

Potential field models of personal space are composed of continuous functions assigning values to positions around humans. These models reflect the idea that personal space intrusion is getting worse the closer the intruder approaches

[1]Felix Lindner, Knowledge and Language Processing Group, Department for Informatics, University of Hamburg, 22527 Hamburg, Germany lindner@informatik.uni-hamburg.de

the human. These kinds of models are based on Gaussians centered at the human's position. The work reported in [9], [8], [11] uses potential field models to avoid personal space intrusion by a robot. The work reported in [6] and [7] proposes potential field models of personal space for the task of robots approaching a human. To this end, three Gaussian functions are blended such that the robot can enter the personal space, move to a particular position relative to the human without getting too close.

Existing models are mainly designed to be used in local path planning algorithms. They successfully solve the problem of avoiding and approaching humans in a socially-aware manner. However, these models are not suited to be used in high-level knowledge processing algorithms like qualitative decision making, task planning, and natural language generation. One consequence is that there is no interface for high-level specifications of robot behavior in personal spaces. A second consequence is that robots cannot make their decisions transparent to humans. In what follows, I suggest a qualitative model of personal space for the use in knowledge-based cognitive social robots.

III. Personal Space as Affordance Space

One aspect that has so far been neglected in personal space modeling is the fact that Hall's characterization of personal space [4] is grounded in the possiblities for interactions between humans. Indeed, Hall claims that two humans feel close to each other because of the potential interactions that are possible ([4], p. 113): "The kinesthetic sense of closeness derives in part from the possibilities present in regard to what each participant can do to the other with his extremities."

Consequently, the regions within personal space (Fig. 1) are labeled in accordance with the type of interactions the regions are normally used for. Hall writes ([4], p. 114): "My choice of terms to describe various distances was [. . .] influenced by [. . .] a desire to provide a clue as to the types of activities [. . .] associated with each distances [. . .]." So, the intimate region is the region at which activities can be placed that are conceived of as intimate, and the personal region is the region at which personal activities can be placed, et cetera. In the following, a model of personal space is proposed that is based on potential activities.

A. Affordances

The theory of potential activities is tightly connected to the notion of "affordance" as coined by the psychologist J. J. Gibson [15]. According to Gibson, affordances are characterized as follows ([15], p. 127): "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill. [. . .] I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment."

Examples for affordances are the possibility to sit on a chair, the possibility to climb the stairs, and the possibility to talk to a human. Gibson claims that being social implies being able to recognize the affordances provided by the environment to oneselves as well as those provided to others ([15], p. 141).

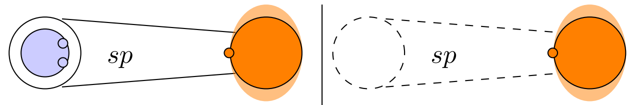
An important thing to notice is that there are several, partly incompatible ways to understand what an affordance is. For the field of robotics, [18] provides a comprehensive overview of how the concept of affordances can be understood. However, what's relevant here is that among theories about affordances, it is common ground that there are properties of the environment, properties of the agents capable of acting and relations between properties of these two kinds. For instance, a chair has certain properties that stand in a certain relation to properties of living beings who can sit on that chair. Some authors claim that affordances are the properties of the environment that have to be complemented by fitting abilities for activities to occur. Turvey [17] is a proponent of this view. I take this view as a basis of the personal space model. Hence, I characterize affordances as properties of the things in the environment an agent can act upon: Affordances *inhere in* objects and living beings. For instance, the possibility to talk to a particular human, i.e., its affordance being talked to, is a property that inheres in that very human. Each time another agent talks to that human, the same talkability affordance gets *realized* by the respective activity. Every activity that realizes some affordance also *uses* an ability of the agent of that activity.

B. Affordance Spaces

Activities that realize affordances require space. Hence, the proposed conceptual model specifies that activities produce activity spaces, which provide an *agent region* occupied by the agent of the activity, a *patient region* occupied by the object or living being that inheres the affordance realized by the activity, and a *transactional region* being the space that is needed beyond agent region and patient region for the activity to be successfully performed. For instance, the activity space produced by a robot talking to a human is composed of the location of the robot (agent region), the location of the human (patient region), and the space between the robot and the human which needs to be kept clear (transactional region). This spatial model of activity spaces is a slightly modified derivative of Kendon's model of transactional segments (cf., [19], p. 210f).

As argued in [16], affordance spaces can be considered as the fundamental spatial concept to model spatial needs of activities. An affordance space is *produced* by an affordance, and activities that realize this affordance are *placed at* one of the affordance spaces produced by it. E.g., the activity of a robot talking to a human is placed at an affordance space produced by the talkability affordance inherent to the human.

Affordance spaces imprint the spatial structure of activities onto space. They have a *potential agent region*, a *potential transactional region*, and an *affordant region*. While an activity is placed at an affordance space, the affordance space becomes an activity space, and, hence, the potential agent region of the affordance space becomes the agent region of the activity space, the potential transactional region becomes the transactional region, and the affordant region becomes the



(a) ACTIVITY-SPACE(sp, t_0) (b) $\neg$ACTIVITY-SPACE(sp, t_1)

Fig. 2. Depiction of an affordance space produced by a human (orange) that can be used by a robot (blue) to talk to the human. (a) An activity is currently placed at affordance space sp, therefore sp is an activity space at t_0. (b) The activity is over, sp is not an activity space at t_1 and ready to be used by another activity.

patient region of the activity space (cf., [16]). This relation between affordance spaces and activity spaces is exemplified in Fig. 2.

Using affordance spaces, the activity placement problem can be solved: Given an activity type ϕ to be performed by a given agent α, the problem is to find a placement π such that α can successfully ϕ at π [14]. To solve this problem under the perspective of affordance spaces, the concept of an *candidate affordance space* is defined: If (and only if) an affordance space sp can be used by an agent α to perform activities of a particular type ϕ, then the affordance space sp is called a candidate affordance space for activities of type ϕ as performed by agent α. Affordances spaces that are produced by humans are candidate affordance spaces for interactions. With reference to Hall's model of personal space, I call these kinds of affordance spaces *Hallian affordance spaces*. The human who inheres the affordance that produces the Hallian affordance space is called *owner of the Hallian affordance space*. A *personal space*, as will be argued further, is an agglomerate of Hallian affordance spaces of a particular human, who will also be called the *owner of the personal space*.

C. Social Properties of Hallian Affordance Spaces

In Sect. I, it is argued that there is a dual use of personal space. On the one hand, personal space is used in the sense of Sommer [21] who claims that there is an area which should not be invaded by other people. This includes situations of unfocused interaction, e.g., strangers passing by or taking the same elevator. On the other hand, Hall [4] analyzes focused interactions and stresses that personal space is grounded in the possibility of interactions between humans.

Considering the distinction between personal space use in focused versus unfocused interactions, Hallian affordance spaces can have two time-variant properties. If it is the case that the owner of the Hallian affordance space sp accepts at time t that agents that are related to the owner in the social relation sr use sp for focused interactions of the type ϕ, then ACCEPTABLE-USE(sp, sr, ϕ, t) holds. If it is the case that the owner of the Hallian affordance space sp prefers at time t that agents that are related to him in the social relation sr and which do not interact with him in a focused way should not be placed in sp, then TOO-CLOSE(sp, sr, t) holds.

Section V gives examples how these two relations ACCEPTABLE-USE and TOO-CLOSE can be used to model acceptable and inacceptable spatial behavior of a robot in concrete situations.

IV. Reasons for Activity Placement

A. On Socio-Spatial Reasons

Hallian affordance spaces can be understood as a discretization of space grounded in the spatial needs of potential interactions. Hence, to place an interaction means to pick one of the available Hallian affordance spaces. In the following, I specify how Hallian affordance spaces and their social properties introduced in Subsect. III-C can be used in the decision process of a social robot. The idea is that humans provide reasons that count in favor of or against placing activities of certain kinds at certain affordance spaces.

The moral philosopher Joseph Raz characterizes reasons as "facts that have [...] force. [Reasons] can serve as stepping-stones in reasoning about what to believe or what to do" ([22], p. 23). Furthermore he claims that "[d]eliberating from the reasons that apply to us we become aware of the attractions and drawbacks of options" (ibid).

According to this characterization, I introduce *socio-spatial reasons*. Socio-spatial reasons *apply to* placing activities at affordance spaces. Every human being *provides* socio-spatial reasons of positive and negative polarity (pros and cons). Hence, the activity placement problem can be solved by making a choice between the available candidate affordance spaces based on the reasons that apply to placing activities at them. In [14], the problem of picking one of the most socially acceptable candidate affordance spaces was called "the social activity placement problem."

B. Two Principles of Placing Activities in Personal Spaces

Knowing about available candidate affordance spaces and socio-spatial reasons provided by humans, what remains is to figure out which of the socio-spatial reasons apply to which candidate affordance spaces, given an interaction to be placed. To establish this relation, two principles are defined:

The first principle of activity placement in personal spaces reads: "Focused interactions should be placed at a Hallian affordance space of which it is known that the human who is the owner of the personal space accepts the use of this affordance space for the given interaction." Thus, at time t the socio-spatial reason $\rho^{+}_{\alpha_1}$ of positive polarity provided by the owner α_1 of the personal space applies to placing an activity of type ϕ performed by an agent α_2 at an Hallian affordance space sp if and only if ACCEPTABLE-USE(sp, sr, ϕ, t) holds and α_2 is in a sr-relation to α_1 at t.

The second principle of activity placement in personal spaces reads: "Activities should be placed such that the personal space of bystanders will not be invaded." Thus, at time t the socio-spatial reason $\rho^{-}_{\alpha_1}$ of negative polarity provided by the owner α_1 of an Hallian affordance space sp_1 applies to placing an activity of type ϕ performed by an agent α_2 at an affordance space sp_2 if and only if TOO-CLOSE(sp_2, sr, ϕ, t) holds, the potential agent region of sp_1 overlaps at t with one of the regions in sp_2, and α_2 is in a sr-relation to α_1 at t.

V. CASE STUDIES

A. Implemented Services

Based on the conceptual model descibed in the preceding sections, two services were realized within a robotic architecture. The first service is called *placement evaluation*. As an input, placement evaluation gets two arguments, an agent α and an activity type ϕ. The result of a service call is an ordered list of all candidate affordance spaces which can be used by α to do activities of the type ϕ.

The placement evaluation service is realized using a decision rule called "Levelwise-Tallying" [20]. This decision rule provably generates a preference order over arbitrary sets of options based on pros and cons of different strengths. For instance, if there are two candidate affordance spaces sp_1 and sp_2 such that there is one strong pro reason in favor of sp_1 and two minor reasons against sp_1, and one strong pro reason in favor of sp_2 and only one minor reason against sp_2, then sp_2 is preferred to sp_1 ($sp_2 \succ sp_1$).

The second service is called *placement explanation*: Given an agent α, an activity type ϕ, and an affordance space sp that is a candidate for placing ϕ-activities performed by α, a representation of the good and the bad aspects of using sp for ϕ-activities performed by α is returned. This service also first queries the reasons that apply to using sp for ϕ-activities as performed by α. To generate explanations, four distinctions are made: First, if there is a reason pro placing ϕ-activities as performed by α at sp, then the explanation for choosing sp is that using sp *respects* the personal space of the owner of sp. Second, if there is no reason pro placing the activity at sp but there is a reason pro placing the activity at another affordance space sp', then the placement *disrespects* the personal space of the owner of sp'. Third, if there is a reason con placing the activity at sp, then the placement *infringes* the personal space of the owner of sp. And fourth, if there is not a reason con placing the activity sp but there is a reason con placing the activity at another affordance space sp', then the placement *considers* the personal space of the owner of sp'.

The result of a placement explanation service call can be used by a social robot to utter justifications and apologies. Facts of respecting and considering justify the placement of the activity at an affordance space, whereas disrespecting and infringing characterize situations in which the agent α, e.g., the social robot, could utter regret.

In the next sections, three case studies are discussed. Each of the case studies was simulated on a 1.8 Ghz laptop computer with 4 GB Ram. The knowledge about affordance spaces, their regions, socio-spatial reasons et cetera was represented using a relational database. The environment was simulated using Gazebo. All runtimes reported below are average runtimes of 100 service calls.

B. Case: Focused Interaction

The first case study demonstrates the application of the first principle of personal space use introduced in Subsect. IV-B. As a first step, the results from the study of Torta and

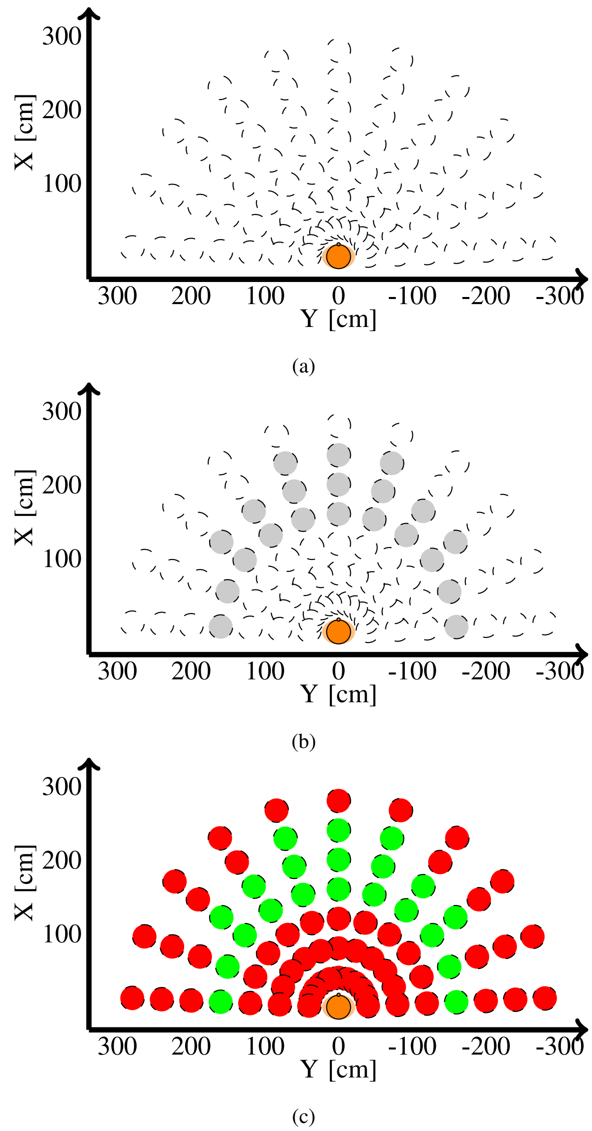


Fig. 3. (a) A (partial) personal space as composed of seventy-seven affordance spaces of which it is known that they can be used by other agents to interact with the human. (b) The potential agent regions of the affordance spaces of which it is known that the human accepts interactions are highlighted grey (matches the Region of Approach found in [2]). (c) The result of a decision process evaluating the available candidate affordance spaces for starting an interaction with the human. The evaluation considers the first principle of personal space use.

colleguages [2] who empirically determine a so-called Region of Approach are modeled. This Region of Approach can also be understood as a personal space model grounded in a very specific type of interaction, i.e., the set of placements a particular social robot should consider if it intends to talk to a human.

Figure 3a shows a human that inheres the affordance of being talked to. For the sake of this example, this affordance produces seventy-seven Hallian affordance spaces which can be used by the robot to talkt to the human.[1] A subset of these Hallian affordance spaces are the preferred ones because

[1]For reasons of clearity the potential agent regions but not the potential transactional regions are depicted in the figures.

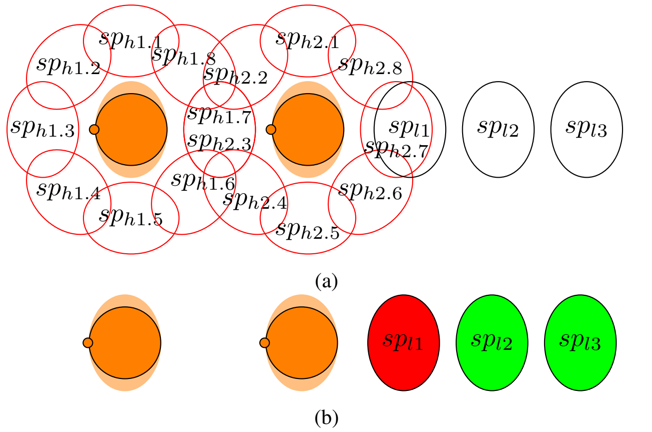


Fig. 4. (a) Two humans standing in line. Each of them has a personal space, i.e., affordance spaces other agents can use to interact with that human. Affordance spaces sp_{l1}, sp_{l2}, sp_{l3} are produced by the line formed by the humans and can be used by other agents for queuing, i.e., to join the line. (b) Due to the second principle of activity placement in personal spaces human h_2 provides a reason against using sp_{l1} for queuing. Thus, using sp_{l2} or sp_{l3} for queuing is preferred to using sp_{l1} for queuing.

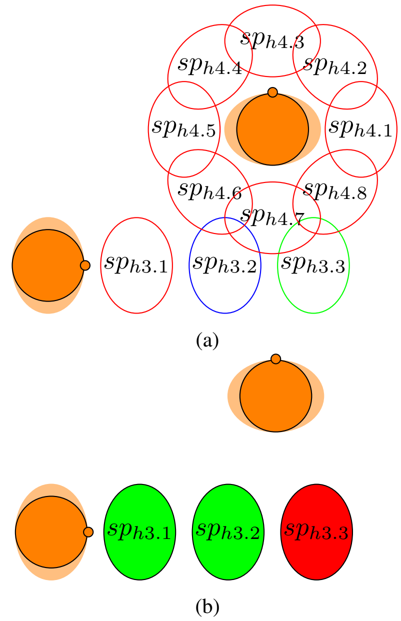


Fig. 5. (a) Human h_4 is standing by passively owning several Hallian affordance spaces which strangers should not enter. For human h_3 three Hallian affordance spaces are depicted. They can be used by the social robot to talk to h_3. (b) The result of the evaluation of the candidate affordance spaces for *talk-to*-activities performed by the social robot.

their potential agent regions are located within the Region of Approach found by [2]. In this example, this is true for twenty-one of them. To represent this symbolically, for each of these twenty-one Hallian affordance spaces sp_i there is a fact ACCEPTABLE-USE$(sp_i, personal\text{-}robot, talk\text{-}to, t)$ representing that the owner of the personal space accepts that his home robot places its interactions of type *talk-to* at affordance space sp_i (cf., Subsect. III-C). The potential agent regions of these acceptable affordance spaces are highlighted grey in Fig. 3b.

To solve the social activity placement problem, the placement evaluation service (see Subsect. V-A) is asked to evaluate the available candidate affordance spaces (see Subsect. III-B) for interactions of the home robot with the human. In the depicted situation, the Hallian affordance spaces whose potential agent regions are within the Region of Approach are preferred, because the socio-spatial reason of positive polarity provided by the human (see Subsect. IV) applies to these candidates but not to the others. Figure 3c depicts this result. The evaluation service took 251 ms.

If asked to justify the placement of its activity in one of the accepted affordance spaces, the robot can query the explanation service which returns that the placement respects the personal space of the human (which is an explanation for why to use it). The explanation service ran 457 ms.

C. Case: Unfocused Interaction

The second case is inspired by [5] and demonstrates the application of the second priciple of activity placement in personal spaces (Subsect. IV-B). Figure 4 depicts two humans queuing. The task for the robot rob is to queue as well. To represent this situation, the knowledge base of the robot contains facts about the Hallian affordance spaces of human h_1 (the left one in Fig. 4) and human h_2 (the right one in Fig. 4). Eight affordance spaces closest to each h_1 and h_2 are drawn with red borders. The robot knows that these affordance spaces should not be entered because their owner feel infringed if strangers intruded them. This circumstrance is represented by facts of the kind TOO-CLOSE(sp, sr, t). For instance, the fact that (at time t) the human h_2 does not want strangers to enter affordance space $sp_{h2.7}$ is represented as TOO-CLOSE$(sp_{h2.7}, stranger, t)$.

Apart from the Hallian affordance spaces, there are three affordance spaces sp_{l1}, sp_{l2}, sp_{l3} produced by the affordance to queue, which inheres in the line (the line is modeled as another object which has affordances). These affordance spaces are represented as candidate affordance spaces for activities of the type *queue* as performed by the social robot. According to the second principle introduced in Sect. IV-B, we have the following situation: Because i) sp_{l1} overlaps in this situation (at t) with $sp_{h2.7}$, ii) the robot is a stranger to h_2, and iii) TOO-CLOSE$(sp_{h2.7}, stranger, t)$ holds, it is also true that the reason con provided by human h_2, ρ^-_{h2}, is a reason against using sp_{l1}. Consequently, the evaluation service orders the three candidate affordance spaces: $sp_{l2} \equiv sp_{l3} \succ sp_{l1}$ (compare Fig. 4b). This was done in 80 ms average runtime.

Let's assume the robot rob places its queuing at sp_{l2}. If asked to explain its choice, the robot invokes the explanation service with arguments sp_{l2}, rob and $queue$. The result is that rob using sp_{l2} for its $queue$-activity considers the personal space of the owner of sp_{l2}. The explanation service took 312 ms to return this result.

D. Case: Focused and Unfocused Interaction

Figure 5 shows a situation in which both principles of personal space use are considered. The robot's task is to talk to the human h_3, who owns three candidate affordance spaces ($sp_{h3.1}$, $sp_{h3.2}$, $sp_{h3.31}$) for *talk-to*-activities performed by the robot. In order to accomplish its task, the robot has to make a choice between the three candidates. To represent that the human h_3 accepts that his robot places *talk-to*-interactions at affordance space $sp_{h3.2}$ the knowledge base contains the fact $\text{ACCEPTABLE-USE}(sp_{h3.2}, personal\text{-}robot, talk\text{-}to, t)$. That the human h_4 does not want strangers to enter one of $sp_{h4.1}$ to $sp_{h4.8}$ is represented by eight facts of the kind $\text{TOO-CLOSE}(sp_{h4.i}, stranger, t)$. The robot is classified as a stranger to h_4 and as the personal robot of h_3.

According to the first principle of personal space use (cf., Subsect. IV-B) there is a reason ρ^+_{h3} in favor of affordance space $sp_{h3.2}$. However, according to the second principle, there is a reason ρ^-_{h4} against affordance spaces $sp_{h3.2}$ and $sp_{h3.3}$. The placement evaluation service orders the candidates: $sp_{h3.1} \equiv sp_{h3.2} \succ sp_{h3.3}$ (in 107 ms).

Let's assume the robot chooses to place its activity at $sp_{h3.1}$. The explanation service returns that this choice disrespects the personal space of h_3 and considers the personal space of h_4 (cf., Subsect. V-A). If the robot chooses to place its activity at $sp_{h3.2}$ instead, the explanation service tells that this choice respects the personal space of h_3 but infringes the personal space of h_4 (in 428 ms). Whatever the social robots' final choice is, this knowledge can be used to communicate to humans that it is aware of the social context.

VI. CONCLUSIONS

The goal of this work is to contribute to the discourse on modeling personal space for social robotics. While most existing models rely on parametrized numerical or geometric representations, this work represents personal spaces in symbolic knowledge bases. Personal spaces are defined based on affordance spaces and thus directly linked to the possibilities for interactions provided by humans.

Using this model, the problem of determining a socially acceptable placement for a robot to interact with a human was mapped to the problem of weighing the pros and cons w.r.t. placing an activity at one of the available candidate affordance spaces. To this end, socio-spatial reasons were introduced. They are provided by humans and apply to placing activities at affordance spaces. Two services were implemented within a robot architecture, viz., a placement evaluation service and a placement explanation service. As demonstrated, a social robot can use the very same representations of personal spaces for decision making and for communicating pros and cons to humans.

So far, the implementation of the model is not intended to be used in high-frequency decision making procedures such as local navigation and obstacle avoidance. That said, the model complements existing models but does not substitute them. Future research will investigate the integration of symbolic representations of personal spaces and their numerical and geometrical counterparts.

REFERENCES

[1] M. L. Walters, K. Dautenhahn, R. te Boekhorst, K. L. Koay, D. S. Syrda, C. L. Nehaniv, An empirical framework for human-robot proxemics, in Proceedings of the Symposium on New Frontiers in Human-Robot Interaction, AISB 2009, pp. 144–149.

[2] E. Torta, R. H. Cuijpers, J. F. Juola, D. van der Pol, Modeling and testing proxemic behavior for humanoid robots, International Journal of Humanoid Robotics, vol. 9(4), 2012, pp. 1250028-1–1250028-24.

[3] Y. Kim, B. Mutlu, How social distance shapes human-robot interaction, International Journal of Human-Computer Studies, vol. 72, 2014, pp. 783–795.

[4] E. T. Hall, The Hidden Dimension, Garden City, New York, 1966.

[5] Y. Nakauchi, R. Simmons, A social robot that stands in line, Autonomous Robots, vol. 12(3), 2002, pp. 313–324.

[6] J. Kessler, C. Schroeter, H.-M. Gross, Approaching a person in a socially acceptable manner using a fast marching planner, in Proceedings of the 2011 International Conference on Intelligent Robotics and Applications, ICIRA 2011, pp. 368–377.

[7] M. Svenstrup, S. Tranberg Hansen, H. J. Andersen, T. Bak, Adaptive human-aware robot navigation in close proximity to humans, Int. Journal of Advances Robotic Systems, vol. 8(2), 2011, pp. 1–15.

[8] R. Kirby, R. Simmons, J. Forlizzi, COMPANION: A constraint-optimizing method for person-acceptable navigation, in Proceedings of the 18th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2009, pp. 607–612.

[9] E. A. Sisbot, L. F. Marin-Urias, R. Alami, T. Simeon, A human aware mobile robot motion planner, IEEE Transactions on Robotics, vol. 23(5), 2007, pp. 874–883.

[10] A. K. Paney, R. Alami, A framework towards a socially aware mobile robot motion in human-centered dynamic environment, in Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2010, pp. 5855–5860.

[11] P. Papadakis, P. Rives, A. Spalanzani, Adaptive spacing in human-robot interaction, in Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2014, pp. 2627–2632.

[12] M. Luber, L. Spinello, J. Silva, K. O. Arras, Socially-aware robot navigation: A learning approach, in Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2012, pp. 902–907.

[13] E. Goffman, Relations in Public – Microstudies of the Public Order, Basic Books, New York, 1971.

[14] F. Lindner, C. Eschenbach, Affordance-based activity placement in human-robot shared environments, in Social Robotics, 5th International Conference, ICSR 2013, Bristol UK, pp. 94–103.

[15] J. J. Gibson, The theory of affordances, in The Ecological Approach To Visual Perception, Hillsdale, NJ: Erlbaum, pp. 127–143.

[16] F. Lindner, C. Eschenbach, Affordances and affordance space: A conceptual framework for application in social robotics, in Sociable Robots and the Future of Social Relations, 1st International Conference, Robo-Philosophy 2014, Aarhus DK, pp. 35–45.

[17] M. Turvey, Affordances and prospective control: An outline of the ontology, Ecological Psychology, vol. 4(3), 1992, 173–187.

[18] E. Şahin and M. Çakmak and M. R. Doğar and E. Uğur and G. Üçoluk, To afford or not to afford: A new formalization of affordances toward affordance-based robot control, Adaptive Behavior, vol. 15, 2007, pp. 447–472.

[19] A. Kendon, Conducting Interaction: Patterns of Behavior and Focused Encounters, Cambridge University Press, 1990.

[20] D. Dubois, H. Fargier, J.-F. Bonnefon, On the qualitative comparison of decisions having positive and negative features, Journal of Artificial Intelligence Research, vol. 32(1), 2008, pp. 385–417.

[21] R. Sommer, Personal Space: Behavioural Basis of Design, Pentice Hall, 1969.

[22] J. Raz, From Normativity to Responsibility, Oxdord University Press, 2011.

[23] F. Dylla, A. Kreutzmann, D. Wolter, A qualitative representation of social conventions for application in robotics, Qualitative Representations for Robots: 2014 AAAI Spring Symposium Series, 2014, pp. 34–41.

[24] R. Tomari, Y. Kobayashi, Y. Kuno, Empirical framework for autonomous wheelchair systems in human-shared environments, in Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, 2012, pp. 493–498.

[25] C.-P. Lam, C.-T. Chou, K.-H. Chiang, L.-C. Fu, Human-centered robot navigation—towards a harmoniously human-robot coexisting environment, IEEE Transactions on Robotics, vol. 27(1), 2011, pp. 99–112.