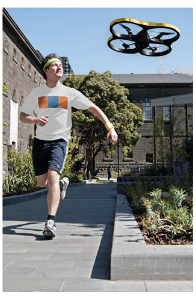
5

Spatial Interaction

What is covered in this chapter:

- The importance of the spatial placement of agents in social interaction.
- Basic understanding of human proxemics: how people manage space in relation to others.
- How a robot manages the space around it, including interactions such as approaching, initiating interaction, maintaining distance, and navigating around people.
- How the properties of spatial interaction can be used as cues for robots.

Figure 5.1 The Joggobot Drone (2012). (Source: Photo provided by Eberhard Gräther and Florian "Floyd" Mueller)



In 2012, Exertion Games Labs released a drone exercise companion called Joggobot (see Figure 5.1). Runners who feel like they could use a little extra motivation or companionship during their run but don't have a personal trainer or a friend to join them can now have a drone accompany them during their exercise laps. One of the critical features of Joggobot is its placement in space during the run: right in front of the runner, like a carrot tempting a running horse. This position wasn't chosen on a whim. The developers studied where the drone should ideally be in relation to the runner (i.e., above, following, leading, on the side) and how much distance it should keep in order to maximize motivation (Graether and Mueller, 2012). They found that having the drone flying behind the jogger made people feel like they were being chased, which decreased their enjoyment of exercising. Users much preferred to take on the chasing role themselves. This shows that the spatial placement of a robot with respect to its user is an important aspect to consider in human–robot interaction (HRI).

Consumer drones, such as the readily available and cheap quadrotor platforms, have become ubiquitous since the Joggobot was developed. Baytas et al. (2019) reviewed the use of drones in social environments, where they fly in close proximity to people and even interact with users, with drones even acting as a teacher in the classroom (Johal et al., 2022). As you can imagine, distance matters in such cases, and proxemics in human–drone interaction is now an active research field (Yeh et al., 2017; Han et al., 2019; Wojciechowska et al., 2019).

Thus, when planning a robot's placement in space, it is crucial to consider people's preferences and the social norms that exist regarding such placement in relation to others. This chapter covers the spatial component of HRI.

Section 5.1 explains the tendencies that humans display with regard to space when they are in a social setting with other humans; Section 5.2 discusses to what extent these social norms and unspoken rules extrapolate to a social setting that includes robots.

5.1 Use of space in human interaction

When space is available, individuals are strongly expected to adhere to social distance norms. Most people feel it is inappropriate for a stranger to sit beside them on an otherwise empty bus. However, when taking the bus during rush hour, we are forced to step into others' personal space, and it becomes acceptable to sit or stand close to others. Even though it is not considered impolite to stand next to someone on a busy commute, people often feel uncomfortable, avoiding eye contact and quickly repositioning themselves at a greater distance when more space becomes available (see Figure 5.2).

Figure 5.2 Commuters during rush hour on the Tokyo subway having their personal space violated. We often deal with this by avoiding the gaze of others.

5.1.1 Proxemics

Cultural anthropologists coined the term *proxemics* to describe how people take up space in relation to others and how spatial positioning influences attitudes, behaviors, and interpersonal interaction. Hall et al. (1968) describe four distance zones in their original work: intimate distance, personal distance, social distance, and public distance (see Figure 5.3). When the available space is (relatively) unlimited, these distances indicate the psychological closeness between people.

As the name suggests, intimate distance is reserved for close personal relationships or the sharing of private information. Intimate distance ranges roughly from a few centimeters to about half a meter, depending on one's age and culture. Together with personal distance (which ranges from about half a meter to 1.2 meters), these zones make up the personal space of a person: the amount of space that people generally consider theirs to take up.

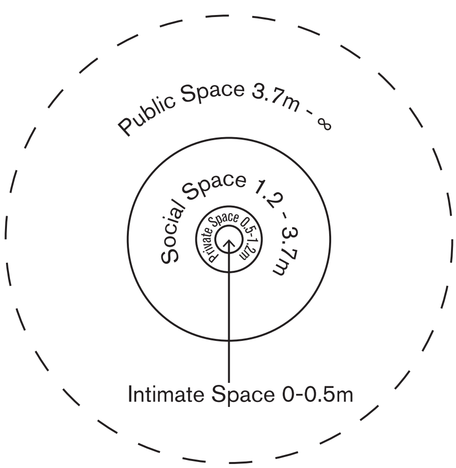


Figure 5.3 Intimate, personal, social, and public distance, according to Hall et al. (1968).

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Under normal circumstances, only friends, relatives, and partners are expected to come this close. For less personal relationships, such as acquaintances or colleagues, one is expected to maintain social distance, which ranges between 1.2 and about 4 meters between persons. Finally, public distance starts at around 4 meters, which is the distance people are expected to keep between them in relatively impersonal settings, such as public speaking at a conference.

Hall et al. (1968) consider people's use of space as an often-overlooked dimension of cultural experience and note that people from different cultures have varying personal proxemic preferences and expectations. For example, in "high-contact cultures," such as those of South America, people will frequently enter each other's personal space and touch, whereas in "low-contact cultures," such as the United States, touching a stranger may be construed as assault. Hall wittily observe that North Americans visiting South America will find themselves "barricading themselves behind their desks, using chairs and typewriter tables to keep the Latin American at what is to us a comfortable distance." (Hall, 1990, p.180)

Slight breaches of proxemic norms are sometimes made on purpose by individuals, for instance, to create more psychological closeness or perhaps to intimidate. For example, a man who nonchalantly places his arm first on the backrest of the sofa where his date is sitting and then cautiously inches closer and closer is making a transition from personal distance to the intimate zone. The friend who touches your arm when you are telling a personal story does the same, although with a different underlying motive. However, these moves have to be made very cautiously and under continuous assessment and reassessment of the reaction of the other person. Few people would be charmed if a hopeful suitor had abruptly placed themselves right on their lap at the start of a date. Likewise, when we attempt to comfort a colleague by giving a hug at the wrong moment, the interaction can turn awkward rather quickly. This is because the meaning of spatial-interaction cues is highly contextual. Unlike the friendly moves just mentioned, an investigator questioning a suspect may "get in the suspect's face" by moving as close to the suspect as possible to seem more threatening.

Not only the distance at which we interact with each other but also our placement in relation to interaction partners are bound by social norms. For example, researchers found that people who sat next to each other were more cooperative, whereas people sitting opposite each other behaved more competitively. During conversations, people usually position themselves at an angle to each other (Cook, 1970). The way in which people place themselves with respect to each other is therefore an important aspect of the dynamics of interaction (Williams and Bargh, 2008).

Finally, circumstances beyond our control can have a profound impact on proxemics. The COVID-19 pandemic, which raged across the globe in 2020, forced us all to adopt social distancing. Social distances that previously seemed fine suddenly made us all feel very uncomfortable. Authorities insisted that we keep a minimum distance of 1.5 meters (or 6 feet) from people who were not part of our household, and people instinctively started avoiding crowds and adopted very different proxemics (Mehta, 2020). Time will tell if the two years during which we were forced to alter proxemics will have a lasting effect on the social distances we keep or if the realities of crowded metros and old habits will force us back into our old ways.

5.1.2 Group spatial-interaction dynamics

The importance of spatial dynamics goes beyond one-on-one interaction and is also salient in group interaction scenarios. The spatial orientation of people in a group in relation to others can make the group seem as if it were inviting more members or seeking to keep others out. For example, at a cocktail party, when people stand in a tight-knit circle, it can seem difficult to join in the conversation. However, if the group notices people wanting to join and opens up the circle so that there is space for new members to fill, it can be construed as an invitation to participate. This type of information can be useful for robots to gauge which groups of people they can approach in public spaces like museums or malls or if they want to join the interaction dynamics of human groups.

Group spatial dynamics such as these were described by Adam Kendon as the "facing formation," or "F-formation" ... defined as "one to which they have equal, direct, and exclusive access" (Kendon, 1990, p. 209) (see Figure 5.4). These formations are created through the positioning of two or more people in relation to each other, such that the areas of space that they are facing and on which they focus their attention are overlapping. The inner space between these people is termed the *o-space*(Kendon, 1990). The group participants themselves are said to occupy the *p-space*, and they are surrounded by *r-space*. People can modify their positions to maintain this space or to include other participants in the group conversation, as in the previous example. Different configurations of the F-formation are possible, based on people's orientation to each other, and are termed the *face-to-face*, *L-shape*, and *side-by-side* formations for two people and the *circular formation* and other shapes for larger groups.

These group formations have been used to understand people's interactions with technology (Marshall et al., 2011) in general and with robots more specifically (e.g., Hüttenrauch et al., 2006; Yamaoka et al., 2010).

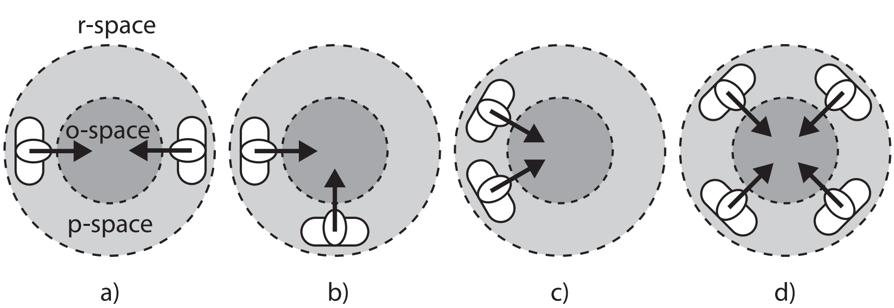

Figure 5.4 Kendon's (1990) F-formations come in several variants, all of which include the components of o-, p-, and r-space, namely: the (a) face-to-face, (b) L-shape, (c) side-by-side, and (d) circular formations.

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In navigation around people, Pérez-Hurtado et al. (2016) found that a robot needs to be aware of people's movements and cognizant of people engaged in conversation and not walk between them even if there is enough space.

5.2 Spatial interaction for robots

Robots will often share physical space with humans. Some robots are mobile, moving over the ground or through the air. Some of them have arms and manipulators so that they can interact with objects and users. The placement and movement of such robots with respect to people must be considered when designing human–robot interactions. Robots that do not respect the personal space of the user will evoke negative reactions or even rejection and withdrawal by the user. Robot designers can attempt to increase acceptance of the robot by having it keep an appropriate distance (assuming that they can code the robot in such a way that it knows what the "appropriate distance" is at a given point in time and space) and adjusting its position to create a fitting interaction experience. For example, a security robot might initially keep a polite distance but enter a person's intimate space at some point in the interaction in an attempt to intimidate the person.

5.2.1 Social navigation

Before going into HRI, let us briefly explain the basic techniques from robotics that are required for a robot in order to engage in spatial interactions with humans. When a robot wants to interact with people, it needs to locate itself in space with regard to the people it aims to interact with. Thus, one of the basic techniques required for mobile robots is localization; a robot needs to know where it is. This is not a trivial problem. A typical robot is equipped with an odometer, a sensor that records the distance traveled by the robot's wheels. However, as the robot travels, these measurements lose accuracy, and the robot therefore needs to correct the information that the odometry provides about its location. The typical solution to this is to let the robot build a map of its environment and then cross-reference information on its location and orientation from the odometry with information from other sensors, such as a laser range finder or camera, to locate itself on the map. This process is known as *simultaneous localization and mapping*, or SLAM (Davison et al., 2007; Thrun et al., 2005).

In addition to reporting the robot's location, localization can help the robot know what type of space it is in (e.g., whether it is in the living room or bathroom). However, it will not reveal anything about the whereabouts of any people in that space. Identifying the location and orientation of people interacting with the robot thus is the next challenge. For detecting people at a short range, the robot will carry sensors, such as two-dimensional (2D) cameras and depth cameras, that enable it to identify nearby people. The software processing the camera images can not only detect and track humans but also report on the location of body parts such as arms, legs, and heads. For tracking people at longer distances, there are techniques that use laser range finders (also known as *light detection and ranging*, or LiDAR). A motion-capturing system is sometimes used. By placing reflective or fiducial markers on people and objects, motion capture can be used to identify and locate the markers (and by extension, the people or objects they were initially attached to). However, these marker-based approaches are difficult to use outside a lab setting: good luck convincing customers to stick markers on themselves to allow their home robot to recognize them. Finally, researchers can also mount sensors, such as cameras, in the environment to track people (Brscić et al., 2013). (For more details on the different sensors that a robot can be equipped with, see Section 3.4 in Chapter 3.)

Moving the robot through a crowded environment, also known as *robot navigation*, is a well-studied problem in mobile robotics. To avoid collisions between the robot and objects or people, techniques such as the dynamic window approach (DWA) are often used (Fox et al., 1997). The idea behind this technique is that a system computes its future location based on the current velocity of the robot while at the same time considering whether to keep or alter its velocity within the limitation of its actuation capability—and while calculating a future velocity that does not result in a collision. Over longer time scales, there are techniques based on path planning. In these techniques, if a given goal of a robot is not within immediate view of the robot, a path-planning algorithm computes a set of way points or paths for the robot that will let it reach its goal. In robotics, most path-planning algorithms that work well for navigating around obstacles will result in socially inappropriate behavior when tried around people. We will discuss the social rules around positioning shortly.

Localization and navigation can also take various elements of interaction with a user into account. For instance, Spexard et al. (2006) developed a robotic mapping technique that uses input from dialogue with users to learn about new places in an environment. To develop a human-friendly mapping technique, Morales Saiki et al. (2011) had a robot explore the environment while collecting visual landmarks to build a cognitive map from a humanlike perspective; this enabled the robot to generate route instructions that people could easily comprehend. Researchers have also worked toward developing techniques to understand human spatial descriptions, such as route directions. For instance, Kollar et al. (2010) developed a technique to associate a user's instructions and visual information about the environment to help the robot interpret the location mentioned by a user. Zhou et al. (2022) first measured how people pass one another in social settings, then implemented navigation behavior for a Pepper robot, showing that people felt more at ease near a robot with socially aware navigation.

5.2.2 Socially appropriate positioning

Even though there are basic techniques for perception and navigation that allow robots to move around without colliding with obstacles, robots still often lack the capabilities to navigate in a socially appropriate way in the presence of other people. Suppose we want a robot to move through a corridor in an office building. What would happen if it considers people as obstacles? When a person walked toward the robot from the other end of the corridor, the robot would continue to move straight down the corridor until inches before colliding, then move out of the way. Although it would avoid a collision with the person, this behavior is very different from what humans would do in a similar situation: we yield to each other well in time, nonverbally showing which side of the corridor we will walk on, and will avoid entering each other's personal space. Thus, a robot waiting until the last moment before moving out of the way may be seen as confrontational or aggressive, even though it still avoids running into a person.

Most mapping techniques for robots only provide geometrical maps, where people are considered obstacles. They do not contain information on which direction people are facing, if they are having a conversation or just standing close to each other, or how people are moving. Hence, there are several techniques that allow a robot to acquire a more human-aware representation of its environment.

One of the focuses in investigating proxemics in HRI has been identifying appropriate interaction distances between users and robots (see Figure 5.5). These include questions like the following: How close do people prefer to stand relative to a robot? How close should a robot approach people before it is considered rude or inappropriate or makes people feel uncomfortable? Walters et al. (2005) measured the distance at which people feel comfortable when they are approached by a robot. They reported that the majority of people prefer a personal or social distance when interacting with a robot, although some people prefer to stand even closer. Hüttenrauch et al. (2006) reported that people preferred the robot to stand at distances derived from human proxemics. Investigating interactions between a robot and a group of people,

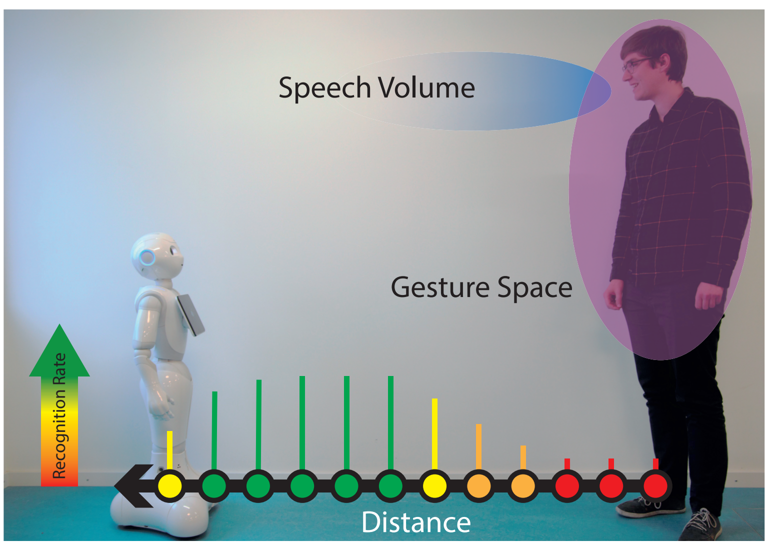

Figure 5.5 A lab setup for proxemics study of HRI.

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Kuzuoka et al. (2010) reported that a robot can change the conversational F-formations of the group by changing its body orientation, and they also found that movement of the robot's whole body was more effective than having the robot move only its head.

Relational position is also important when people and robots interact while they are moving. To enhance a robot's social acceptability, techniques have been developed for robot navigation based on human proxemics. For instance, when a robot follows a user from behind, the robot can either follow the same trajectory as the user, or it can move directly to the user's current location, which might be a shorter and faster pathway. Gockley et al. (2007) showed that users perceive the first behavior as more natural. Morales Saiki et al. (2012) developed a technique that allows a robot to navigate side by side with its user, for which they found it important for the robot to anticipate the user's future motion.

Furthermore, people's perceived safety does not necessarily correspond to what a robot computes to be safe. For instance, in the corridor passing problem, it was found that a robot needs to maintain enough distance to avoid entering a person's intimate zone (Pacchierotti et al., 2006). Alternatively, a robot can mimic how people avoid colliding with each other. Luber et al. (2012) and Shiomi et al. (2014), for example, developed a pedestrian model that implemented collision avoidance for dynamic environments. Considerations of comfort and perceived safety can also be integrated into path planning. Sisbot et al. (2007) developed a path planner for a mobile robot that plans how to reach a given goal while avoiding situations that might make people uncomfortable. The planner takes into account aspects such as whether people are sitting or standing and whether the robot might surprise them by suddenly appearing from behind an obstacle. Fisac et al. (2018) used a probabilistic model of a human walking to plan and execute a safe trajectory for an indoor drone (see Figure 5.6).

Planning a motion path that people will perceive as safe and comfortable is also necessary when only a part of the robot enters the user's personal space. For example, when a robot arm is used near a person, such as when a person

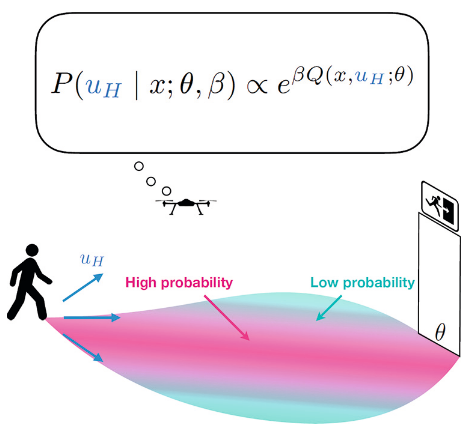

Figure 5.6 The drone calculates a probabilistic model of where the human will go and plans a safe route to avoid collision. (Source: Illustration by Jaime Fernández Fisac, Andrea Bajcsy, Sylvia L. Herbert, and David Fridovich-Keil, depicting their work in Fisac et al. (2018))

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and an industrial robot collaborate on a shared task, the robot must take the socially appropriate distance into account when computing a path for its end effector (e.g., hand) to reach its given goal (e.g., grasp an object or hand an object to a person) (Kulic and Croft, 2005). This may make the robot's movement inefficient from a purely functional standpoint, but it will lead to a more positive evaluation of the interaction by the user (Cakmak et al., 2011).

5.2.3 Spatial dynamics of initiating HRI

Every social interaction has to be initiated by someone, perhaps by hovering in the vicinity of the person you want to talk to at a cocktail party while orienting your body toward the person, for example, or by approaching a colleague to hand over the annual report. How you approach each other and how the approach is perceived have implications for the ensuing interaction.

Approaching behavior is generally expected to have positive effects on both parties in the interaction. The approacher makes an effort to attract and share attention, which signals interest in the person being approached. At the same time, initiating an interaction triggers neural activity in reward-related brain areas, resulting in positive affect in the initiator (Schilbach et al., 2010). Initiating interaction is, furthermore, a sign of being assertive and having faith in one's capability to conduct a successful social encounter. What may be more surprising is that this runs the other way, too. People who approach others are seen by their peers as having more personal control (Kirmeyer and Lin, 1987).

Imagine the moment when a person meets a robot for the first time. Either of them could approach the other to initiate the interaction. Whereas this can be rather trivial for a person, a robot needs to be carefully designed to appropriately initiate an interaction. Approaching behavior for robots has been studied from early on in the field of HRI. For instance, in a situation where a robot joins a queue, the robot needs to respect the personal space of other people who are also waiting (Nakauchi and Simmons, 2002). When a robot encounters people, it needs to switch its navigation mode from purely functional to considering social distance and spatial configuration (Althaus et al., 2004).

Initiating an interaction is also context and task dependent. Satake et al. (2009) show how a robot offering information about the stores in a mall will fail to initiate an interaction if the approach is poorly planned and executed. The planned trajectory needs to be both effective and acceptable to human visitors (Satake et al., 2009; Kato et al., 2015). Whereas approaching from the front was found to be desired when a robot was trying to initiate a conversation, approaching from the front when the robot was delivering an object to a person was less preferred and resulted in more failures (Dautenhahn et al., 2006; Shi et al., 2013).

Some recent work incorporates machine learning to generate appropriate approaching behaviors that fit with a context. Liu et al. (2016) designed approaching and initiating behavior for a store clerk robot using a fully automated analysis of observed human behavior. The researchers first recorded

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how people moved and talked in a camera store scenario and then used machine learning to extract typical speech behavior and spatial formations. These behaviors were then transferred to the robot. A user study showed that the learned speech and motion behavior was considered to be socially appropriate by users.

Even in the case where a person approaches a robot, the robot should respond at just the right moment. If it fails to do so, the user could find the interaction unnatural and awkward and might even give up initiating interactions in the future (Kato et al., 2015). Human proxemics studies, particularly observational studies on the interactions of humans with either one another or with robots, can provide more contextually attuned and relevant models. For instance, Michalowski et al. (2006) developed a categorical model of human spatial interaction and engagement with a receptionist robot from observations of people's interactions with the robot. They defined the appropriate timing and types of behavior (e.g., turning toward a person, saying hello) that the robot could perform with people in different spatial zones in order to both be perceived as more approachable and successfully initiate an interaction when appropriate.

Social navigation has become particularly relevant in the context of self-driving cars. The story goes that the first self-driving cars at Google drove optimal trajectories following the highway code, but they frequently startled other road users by driving too close or cutting them off. Only when politeness was explicitly added as an optimization criterion did the cars drive in a way that was socially acceptable.

5.2.4 Informing users of a robot's intent

Robot motion trajectories are often used to convey the intent and goal of the robot. Path-planning algorithms have been developed to explicitly convey information through the robot's trajectory. For instance, by slowly passing a few meters from a visitor, a mobile robot is able to express whether it is available for an interaction (Hayashi et al., 2012). Similarly, trajectories have been used as a means to allow a robot with few options to express itself, such as cleaning robots and drones, to communicate their intent to users (Szafir et al., 2015).

During handover in HRI, that is, when a robot hands an object to its user, users prefer a robot to behave with "legibility"—in a way that allows users to understand its goal and intention (Koay et al., 2007a). Hence, researchers have developed algorithms to control a robot arm to generate legible motions while reaching a given goal. A robot could hand over an object to a person in many different ways, but the most energy-efficient way may be incomprehensible to a person, so it is better to perform a motion that is easier to interpret (Dragan et al., 2013).

When a robot works closely with a person, it needs to have the capability to understand how the person is perceiving the space around him or her. An important related capability is spatial perspective-taking (Trafton et al., 2005).

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Imagine a situation where two people are working together. One might ask the other to pass an object by saying, "Give me that object." The referent of "object" will be obvious if there is only one object available. But what if there are several objects? For people, inferring the intended referent of "object" is often easy. We may use a complex set of cues, including gaze direction, body orientation, the prior context of the interaction, knowledge about the person and his or her preferences, task information, and other cues, to disambiguate the request. For a robot, however, this can be rather complicated. Several approaches exist that allow the robot to take the perspective of the user. These often rely on geometric models that keep track of the location of people, robots, and objects and which of these are visible and reachable by whom (Lemaignan et al., 2017; Ros et al., 2010).

5.3 Conclusion

The study of spatial interaction in HRI is often inspired by our understanding of human proxemics, conversational relations, and relational positioning and approach behaviors, although we cannot expect the effects to always be the same. However, norms and understandings that are common knowledge for people—to the point where they may not even be aware of them anymore—often turn out to be not so trivial to incorporate into robot behavior. For instance, people will unconsciously and effortlessly adjust the distance to their conversation partner to an appropriate amount; however, a robot would need to conduct a careful computation to decide what distance it should keep during an interaction with its human counterpart. Even more difficulties are involved when the interaction is more complex, for example, when a robot has to approach a person, when it has to maintain spatial formation during a conversation, or when it has to navigate together with a person on the move. These considerations are important not only for achieving socially acceptable and comfortable HRI but also for ensuring that people understand the robot's intentions and can engage with robots safely in their physical space.

Questions for you to think about:

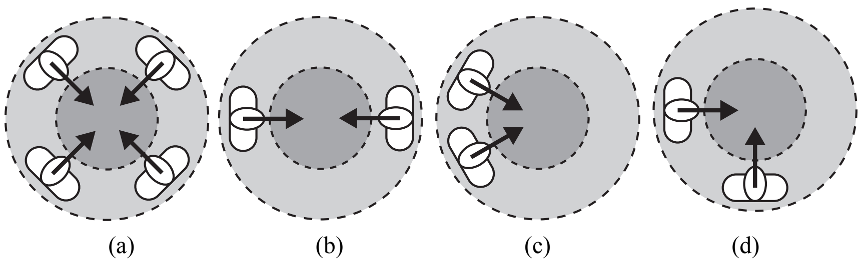
- Let's role-play: To understand how much social information is involved in creating socially appropriate navigation, try to behave like a dumb robot that does not process any social information about space when interacting with a friend (maybe inform your friend beforehand, or "forget" to do so for a more natural response). What happened? How long could you keep this up?
- Think back to a situation when somebody violated your personal space. How did you notice? What was your reaction?
- Imagine you are an engineer building a robot. This robot will come to the market in Japan, Mexico, and the United States. Will the product

be the same for every country? Will the robot's spatial-navigation behaviors differ? If so, how?
- Think about the use of a robot in various daily situations (e.g., at home, at the office, and on a crowded train). Now, think about how you need to adapt the spatial-navigation behavior of the robot to fit each of these contexts. What would be important factors to consider in these different contexts?

5.4 Exercises

The answers to these questions are available in the Appendix.

*** Exercise 5.1 Formations** Group spatial dynamics, as shown in the accompanying diagram, were described by Adam Kendon (1990) as the "facing formation," or "F-formation." For this question, associate the four images (a, b, c, d) with their formation names.



1. Circular formation: ______
2. L-formation: ______
3. Face to face: ______
4. Side by side: ______

**** Exercise 5.2** What is the typical maximum distance for social space?

**** Exercise 5.3** What is the typical maximum distance for personal space?

**** Exercise 5.4** What is the typical maximum distance for intimate space?

**** Exercise 5.5** What is the typical minimum distance for public space?

***** Exercise 5.6 Spatial navigation** Robots are physically embodied, so they not only take up space but also need to be able to navigate it appropriately along with humans in everyday interaction. Based on your own experiences with spatial interaction, as well as the chapter you just read, imagine how you would design a "socially intelligent" Roomba-like vacuum cleaner. What might this mobile robot need to know, and how should it adapt its behavior to socially navigate the context of your home? What kinds of actors, activities, social norms, preferences, and so forth would it need to be aware of? What aspects of its behavior should it adapt to fit the context? Now consider a similar robot outside the home, for example, a food delivery robot that drives on city streets. What kinds of spatial knowledge and behavioral adaptations does this robot need to make so as not to inconvenience passersby and to be able to comfortably approach the person it is trying to make a delivery to?

Future reading:

Textbook to learn basic techniques for robot navigation:

- Choset, Howie M., Hutchinson, Seth, Lynch, Kevin M., Kantor, George, Burgard, Wolfram, Kavraki, Lydia E., and Thrun, Sebastian. *Principles of Robot Motion: Theory, Algorithms, and Implementation*. MIT Press, Cambridge, MA, 2005. ISBN 978-026203327. URL http://worldcat.org/oclc/762070740

More reading about space-related studies in HRI:

- Kruse, Thibault, Pandey, Amit Kumar, Alami, Rachid, and Kirsch, Alexandra. Human-aware robot navigation: A survey. *Robotics and Autonomous Systems*, 61(12):1726–1743, 2013. doi: 10.1016/j.robot.2013.05.007. URL https://doi.org/10.1016/j.robot.2013.05.007
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