EPFL Technical Report
IC/2005/038

DO PARTNERS CARE ABOUT THEIR MUTUAL LOCATION? Spatial awareness in virtual environments

Nicolas Nova, David Traum, Lydia Montandon, David Ott and Pierre Dillenbourg

Center for Research and Support of Training and its Technologies

nicolas.nova@epfl.ch

July 2005

Abstract : This paper reports on four experimental studies concerning regard to how people use space so as to solve problems collaboratively in virtual environments. Prior to presenting the results, it summarizes the wide range of literature concerning social uses of spatiality in human interactions. The experiments we conducted revealed that virtual space modifies and improves collaborative processes such as division of labor, grounding, communication, coordination, as well as the performance to the task. It concludes by proposing Computer Supported Collaborative Work practitioners' ideas about how to use these results in order to design more effective and more adapted environments.

Keywords : CSCW, awareness, virtual space, spatiality, games, MOO, collaboration, coordination.

Introduction

For several decades researchers and engineers proposed to use the spatial metaphor in order to support human-computer interactions. The use of the desktop metaphor is an example of how software interfaces could be spatially organized to increase the ease of use and an intuitive way of presenting information, based on our experience of the real world. The field of Computer Supported Collaborative Work also relies on spatial metaphors to support multi-user interactions. As a matter of fact human beings often use space as a support for social interactions as expressed by Edward Hall's (1966) work on proxemics and social uses of space.

Psychological studies of virtual space have dealt with a wide range of topics from perceptive issues (Witmer et al., 1996) to how people feel to be "present" in virtual space (Lombard and Ditton, 1997). In this sense, the notion of spatiality has received a large amount of interest, especially when dealing with spatial metaphors and information visualization (Risden et al., 2000) or navigation in 3D virtual environments (Jul and Furnas, 1997). Our contribution addresses this issue under another angle: does a spatial metaphor significantly impact the way people perform collaborative tasks. We address this issue from a social perspective: to what extent do users care about their mutual position in space, that is to say how do they maintain mutual knowledge regarding their respective locations. Our main hypothesis is that being aware of the partner's position is meaningful with regard to the joint task carried out by the participants.

The concept of virtual space here refers to computer environments that allow distant users to gather, work, play or learn through different applications. In the context of our experiments, we used namely two types of virtual environments. The first type, which was used in the two first experiments, was a Multi-user dungeon Object Oriented (MOO). A MOO is a text-based virtual reality where users can move and communicate in a virtual space consisting of various rooms. The second type, which was used in the two last experiments, are 3D environments in which people are represented by avatars moving in a world inspired by reality.

Prior to showing how spatiality impacts on collaborative problem solving, a short literature review will present how people rely on space for social interactions in both real and virtual settings. We then report four laboratory studies in which pairs of users had to solve different tasks in different virtual environments. These studies enabled a detailed analysis of collaborative processes and spatial coordination, as one aspect of the process of building a shared solution. To meet this end, we used different collaborative virtual environments ranging from textual and virtual reality (MOOs) to 3D video games. The point was not to compare the specificity of each environment but rather to verify if some results found on MOOs in an exploratory study still held in 3D collaborative virtual environment. As described in figure 1, the starting point of this paper was an exploratory study of how people carry out spatial coordination in virtual space when solving a problem collaboratively. Experiment 2 investigates whether implicit or explicit information about the partner's location modifies group coordination. Then, experiment 3 looks further into one result coming from the first study: how space is used to improve referential communication between participants. Finally, the last experiment intends to reveal how the use of explicit information about the partner's position could improve collaboration and mutual understanding during a joint activity. In the conclusion we discuss these findings and shortly present how space should be taken into account in CSCW systems design.

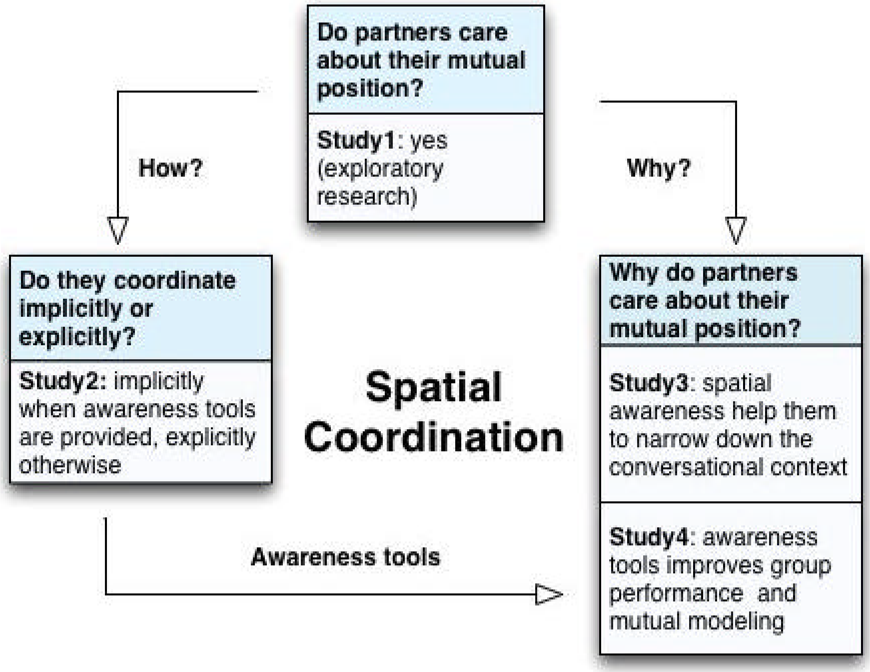


Figure 1: Reading guide of the paper, each experiment fosters new ideas to build the following ones.

Functions of Space

In the real world, space impacts on our behavior in some functional ways (e.g. we cannot cross walls) and also by social uses (e.g. one should not sleep in one's office). A virtual environment reproduces some of these functional constraints (e.g. users must use doors to leave a room), but not all of them (e.g. tele-transportation is possible). Cognitive research traditions have strongly concentrated on space as a basis for abstract thought (Gattis, 2001 for instance) studying the use of space on memory (Yates, 1969) and peculiar aspects of problem solving (Kirsh, 1995).

While many studies concern the relationship between space and individual cognition, we are concerned rather by social interactions. We focus on the socio-cognitive roles of space in both physical settings and virtual worlds when available. The following discussions reflect that space is filled with people, artifacts; it is also the place where activities are performed by individual making use of those tools. Therefore, we consider three dimensions: *persons, space/place and artifacts*, and a corollary feature, which is *activity*. From the relation between each of those components, affordances of space emerge among the group. The following paragraphs will describe these uses of space fostered by all those dimensions.

Person to person relationships in space

Proxemics is the term coined by Edward Hall (1966) to describe the social use of distance between individuals in the physical world. He also defines the concept of personal space, which is the area with invisible boundaries surrounding an individual's body. This area functions as a comfort zone during interpersonal communication. It disappears in particuliar environments (elevator, crowd). Distance between people is a marker that both express the kind of interaction that occurs and reveals the social relationships between the interactants. Several scholars (Jeffrey and Mark, 1998; Krikorian et al. 2000) show that the notion of personal space also exists in virtual environments (like 3D worlds: Active World or Online Traveler). They found that physical proxemics of the real world are reproduced into social interactions that occur in virtual environments.

Besides, the use of virtual space also brings into prominence the notion of embodiment. In collaborative virtual environment, especially the 3D spaces, users are depicted by avatars. Those avatars represent people with stylized pictorial representations of bodies (Benford et al., 1995). Avatars hence embed identity information and seeing this body representation in the virtual space tells one where the distant avatar is located. In addition, the avatars convey information where it is looking through face position or where it is pointing through hand position (Fraser, et al., 1999).

In addition, proximity is also fundamental (Kraut et al., 2002). It refers to the low distance between the participants of a team. Proximity improves various processes like conversation initiation. It is easier in physical settings than in mediated communication since it increases frequency of communication, the likelihood of chance encounter and hence community membership and group awareness thanks to informal conversations triggered by repeated encounters. Using other media to initiate communication is however possible, namely with buddy lists (who is available in the chat room). Spontaneous communication is less frequent in this situation. Chance encounters as well as informal conversations are also supported in virtual communities on the web (Gross, 2002). The second effect of proximity is that conducting conversations in collocated settings is far easier because it allows the use of different paralinguistic and non-verbal signs or turn-taking coordination. Concerning the use of other media to conduct conversations, Clark and Brennan (1991) pointed out different costs: emitting the message, changing speakers, repairing misunderstanding and so forth. A corollary problem in virtual environment concerns the use of voice communication (like voice over IP). It indeed makes possible for users of distributed environments to talk to each other. Nevertheless, it is often hard to know who is talking. It has been found that this could be detrimental to team coordination in multiplayer video games (Halloran et al., 2004).

Furthermore, distance between people has great influence on friendship formation, persuasion and perceived expertise (Latané, 1981). His study shows that people are more likely to deceive, be less persuaded by and initially cooperate less with someone they believe to be distant. Moon (1998, 1999) also revealed that the perceived physical distance has a negative impact on persuasion in computer-mediated communication. Finally, Bradner and Mark (2002) examined how geographic distance affects social behavior when people use computer-mediated communication. They found that people are more likely to deceive, be less persuaded by and initially cooperate less with someone they believe to be distant. In their experiments, even though participants initially cooperate less with remote partners, their willingness to cooperate increases quickly with computer-mediated interaction.

Person and artifacts relationships

Another issue about spatiality is the relationships between people and artifacts located in the vicinity of the participants during social interactions. Indeed, when a speaker talks about an object to his hearer, they are involved in a collaborative process termed referential communication (Krauss and Weinheimer, 1966; Clark and Wilkes-Gibbs, 1986), which the speaker tries to get the hearer to identify the object that he has in mind. In this respect, spatial features like proximity, salience and permanence are often used in order to select reference objects and frames (Tversky and Lee, 1998). As a matter of fact, the practice of pointing, looking, touching or gesturing to indicate a nearby object mentioned in conversation is also used on a regular basis. This process is called deictic reference. Besides, this spatial knowledge can thus be used for mutual spatial orientation. Schober (1993) points out that it is easier to build mutual orientations toward a physical space (versus a shared conceptual perspective) because the addressee's point of view is more easily identified in the physical world. There has been very little research focusing on referential communication in virtual space. Computer widgets, like “What You See Is What I See” have been designed in order to support this process. However some studies showed that tele-pointers or partner's mouse motion are not as powerful as deictic hand gestures (Newlands et al., 2002). They found less deictic act in computer-mediated interaction. Researchers also attested that it is actually more difficult to see where avatars are pointing in 3D virtual environment compared to the real world (Fraser et al., 2000).

Another relevant topic is how people organize tools and objects in space. When manipulating artifacts, human beings organize information spatially so as to simplify perception and choice, and to minimize internal computation in the physical world (Kirsh, 1995) as well as in virtual and augmented reality environments (Biocca et al., 2001).

Person and space relationships

When dealing with people and location, the fundamental use of space concerns human territoriality. It reflects the personalization of an area to communicate ownership. Territories as specific context support social roles among a community (Prohansky et al., 1970). Therefore the meaning of a particular place is endowed through its exclusive use. For each place thus corresponds a set of allowed behaviors. There is a strong inter-relation between group identity (feeling that we belong to a larger human group) and spatial identity (based on our habits, experience and knowledge about the environment). Jeffrey and Mark (1998) found that territoriality was an important feature in the context of virtual worlds. For example, building one's house in Active World is a way “*to provide a territorial marker and provide a feeling of ownership for the owner*” (Jeffrey and Mark,1998:30). Furthermore, it seems that people build their house in existing neighborhoods rather than in uninhabited places.

Additionally, territoriality could be defined as a way to achieve and exert control over a segment of space (Prohansky et al., 1970) and then to maintain and achieve a desired level of privacy. According to Minami and Tanaka (1995, p. 45), "*Group space is a collectively inhabited and socioculturally controlled physical setting*". The activity then becomes a group activity in terms of interactions with and within space as well as control to the degree of space maintaining. Therefore, territoriality is linked to trust. Studies concerning neighborhood and social networks showed that people may trust one another simply because they live in the same neighborhood (Edney, 1976). Unlike interaction in the physical world, trust is much more difficult to maintain in remote interactions over the Internet (Rocco, 1998).

Another concern linked to the topic of human territoriality deals with the visibility and the permeability of its boundaries. There are not only fixed and impermeable communities' perimeters (closed by walls for instance), but also invisible temporary group territories. Small conversing groups in public places are an interesting example: the fixed barriers are replaced by what Lyman and Scott (1967) calls "*social membranes*". Knowles (1973) studied which factors affect the permeability of those invisible boundaries. Using spatial invasions, he showed that people tend not to invade other group territories even if they are in a public space or path (Knowles, 1973). Furthermore, Cheyne and Efran (1972) found that group spaces feel invaded if the boundaries become fuzzy or if the distance among group members becomes large. If this distance is above four feet, the boundary becomes ineffective and passers by begin to walk through the group. Space thus models group interaction. Agreements on spatial territory (Lyman and Scott 1967) or the closeness of members (Cheyne and Efran, 1972) are examples of rules that govern group interaction.

Finally another interesting example is the "rendezvous problem" faced by two non-communicating persons who wish to meet at a common location. Schelling (1960) claims that those people have a common culture that can produce "*focal points*" which enable them to distinguish among several meeting points. Applied to spatial coordination, a Focal Point is an informal location where people are likely to meet each other. Moreover, landmarks have always been recognized for their powerful role concerning navigation in both physical and electronic environments (Sorrows and Hirtle, 1999).

Space, place and activity

Harrison and Dourish (1996) advocated for talking about place rather than space. They claim that even though we are located in space, people act in places. By building up a history of experiences, space becomes a "place" with a significance and utility. A place affords a certain type of activity because it provides the cues that frame participants' behavior. In a sense, it is the group's understanding of how the space should be used that transform it into a place. Space is turned into place by including the social meanings of action, the cultural norms as well as the group's cultural understanding of the objects and the participants located in a given space.

Partitioning activities is another social function supported by spatiality (Harrison and Dourish, 1996). Chat rooms are for example used to support different tasks in collaborative learning: a room for teleconference and a room for class meetings (Haynes, 1998). Research concerning virtual place also claim that a virtual room could define a particular domain of interaction (Benford et al. 1993). Different tasks correspond to virtual location: room for meetings related to a project, office rooms, public spaces and so on. Fitzpatrick et al. (1996) found that belonging to different virtual places provides a support for structuring the workspace into different areas to switch between tasks, augment group awareness and provide a sense of place to the users.

What is also interesting with regard to human activity is the notion of Social Navigation. According to Dourish and Chalmer's seminal paper (1994), it describes situations in which a user's navigation through an information space is guided and structured by the activities of others within that space. They define social navigation as "*navigation towards a cluster of people* or *navigation because other people have looked at something*" (Munro and Benyon, 1999, p. 3). Social space is built considering the traces left in the environment (virtual or not) by people's activity. We all leave signals into social space that can be decoded by others as trace for a potential use: fingerprints, public crowds, recommender systems, graffiti, annotations and so on. From those cues, one can infer powerful things: others were here, this was popular, where can I find something, and so forth. This process exists in both virtual and physical settings through recommender/voting systems or collaborative filtering.

It is obvious to say that physical settings constrain social interactions and conversely those interactions modify space. For instance, seating arrangements appear to influence the interaction patterns (Hare & Bales, 1963) by determining with which participant an individual is likely to interact. Besides, individuals in a circular seating arrangement interact more with individuals opposite rather than adjacent (Steinzor, 1950). When considering group formations in virtual space (3D virtual world in particular), avatars often position themselves face-to-face and in a circle (Jeffrey and Mark, 1998).

Additionally, an important characteristic of places is their visibility. It is indeed possible in the physical world to understand the character of a place from the outside. Bruckman and Resnick (1995) takes the example of a biker bar to show that it is possible to see from the street what kind of place it could be. In the context of virtual world, visibility is much more difficult to support, apart from 3D virtual world.

Space and artifacts

Objects that occupy spaces do have a certain state and location that may be modified. To begin with, being in the same room provides access to the same tools (Benford et al., 1993). This is definitely obvious in physical settings. In virtual space like chat, users could also be provided with tools like shared board in different places. Chatting while using a board is hence possible as in the real world. Besides, the use of a "room metaphor" to structure data in virtual environment has been advocated by lots of academics (Henderson and Card, 1986; Greenberg and Roseman, 2003).

To broaden the view, there are a lot of examples of formal situations where spatial relationships between people and objects are used to reinforce social distinctions and thus to mould the kinds of social interaction to be expected within the spaces (Joiner, 1976). Joiner's studies about small office spaces reveal that room settings (furniture and artifacts) convey information about the occupant as well as how the occupant would like visitors to behave when in his room.

All the uses of space presented here should be seen as "social connotations" as pointed out by Dieberger (1999). This term refers to socially shared understanding of space based on cultural experience of the physical world as well as virtual spaces. It is to be noted that spatial properties do not necessarily map well from physical space to virtual space. Indeed, even though we find proxemics, co-presence, and neighborhood and close spatial interaction patterns in both settings, strong differences do remain. For instance, one of the main differences is the lack of perceptible cues in virtual environments (Bowers et al., 1996): it is really difficult to provide perceptibility of another person's focus of attention in virtual space.

Experimental Studies Reports

The studies presented show that space has an impact on social interactions. In the following sections, we will summarize four experimental studies that show in which way spatiality is used in collaborative task in the context of virtual environments.

First empirical study: Bootnap

The first study was not designed specifically to address the issue of spatial coordination but mainly aimed to study how a whiteboard supports mutual understanding (Dillenbourg & Traum, 1997). However, the data collected revealed some interesting phenomena with respect to spatial aspects.

Experimental setting

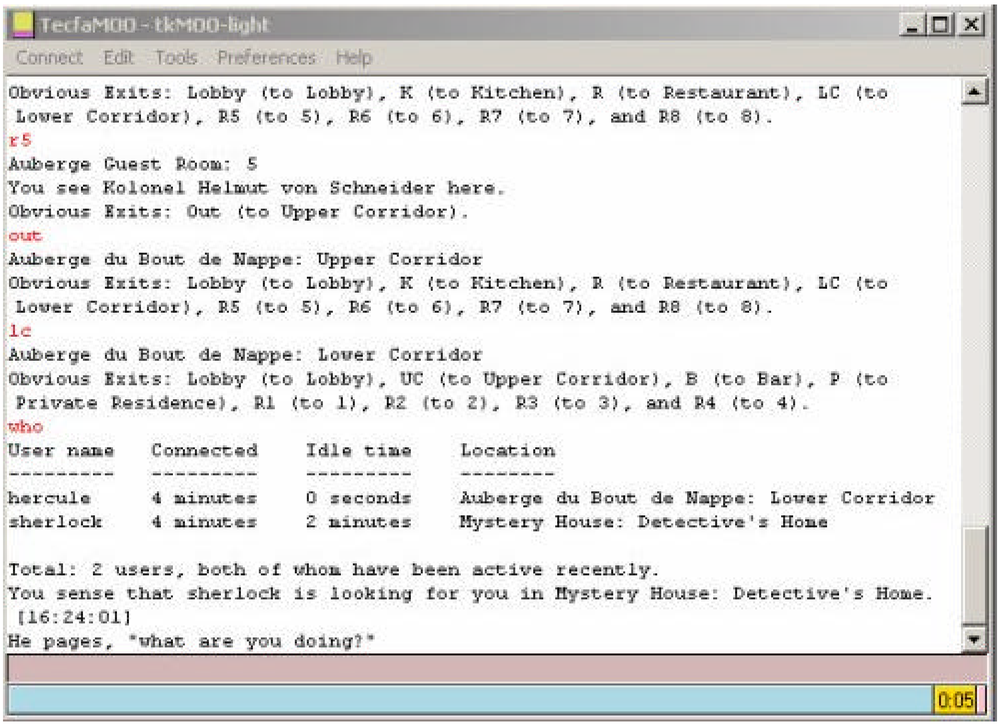
In this experiment, participants played a game in a Multi-user dungeon Object Oriented (MOO) environment. A MOO is a text-based virtual reality where users can move and communicate in a virtual space consisting of various rooms. It is basically a chat box (multi-user synchronous written communication) user access through a MOO client as depicted on figure 2. The chat box is enriched with a spatial metaphor and the possibility to interact with objects. Space is here treated as a social construct rather than from the perceptual standpoint; the rooms are not described by images but only by text. Each of these rooms delimits a private conversation space. People could talk together inside the same room or across different rooms. All the objects and the rooms in the environment were described with short pieces of text, which were usually pre-stored. Moreover, objects maintained a state, which could persist from session to session, allowing extended collaboration. In MOOs, the user perception of space and objects is textual; hence users just rely on his or her mental imagery. This is why the scene is very briefly described and the envisioning process relies heavily on naming the rooms by analogy with familiar spaces (offices, bars, meeting rooms,...).

The two subjects played detectives in a mystery solving game: Mona-Lisa has been killed and they have to find the killer. They walked in a virtual inn where they met suspects, asked questions about relations with the victim, what they had done the night of the murder, and so forth. Suspects were small MOO agents able to answer to a few pre-defined questions. When exploring rooms, detectives also found various objects, which helped them to discover the murderer. They were told that they had to find the single suspect who (1) had a motive to kill, (2) had access to the murder weapon and (3) had the opportunity to kill the victim when she was alone.

The subjects communicated through the Internet, each using a MOO client (tkMOO-light[1]) as presented in figure 2. As well as the standard MOO facilities, each detective carried a special "detective's notebook" which automatically recorded the answers to all the questions that they ask to suspects. They could also merge the contents of their two notebooks or exchange them to find out directly what the other has been told. The MOO client also contained a shared whiteboard: both users drew on the same page, could see and edit the objects drawn by their partner, but they did not see each other's cursor.

---

[1] the MOO client may be downloaded here: http://www.awns.com/tkMOO-light/



```
Obvious Exits: Lobby (to Lobby), K (to Kitchen), R (to Restaurant), LC (to
 Lower Corridor), R5 (to 5), R6 (to 6), R7 (to 7), and R8 (to 8).
r5
Auberge Guest Room: 5
You see Kolonel Helmut von Schneider here.
Obvious Exits: Out (to Upper Corridor).
out
Auberge du Bout de Nappe: Upper Corridor
Obvious Exits: Lobby (to Lobby), K (to Kitchen), R (to Restaurant), LC (to
 Lower Corridor), R5 (to 5), R6 (to 6), R7 (to 7), and R8 (to 8).
lc
Auberge du Bout de Nappe: Lower Corridor
Obvious Exits: Lobby (to Lobby), UC (to Upper Corridor), B (to Bar), P (to
 Private Residence), R1 (to 1), R2 (to 2), R3 (to 3), and R4 (to 4).
who
User name   Connected   Idle time   Location
---------   ---------   ---------   --------
hercule     4 minutes   0 seconds   Auberge du Bout de Nappe: Lower Corridor
sherlock    4 minutes   2 minutes   Mystery House: Detective's Home

Total: 2 users, both of whom have been active recently.
You sense that sherlock is looking for you in Mystery House: Detective's Home.
 [16:24:01]
He pages, "what are you doing?"
```

Figure 2: example of the MOO world accessed through a MOO client (tkMOO-light). In this example, one can see at the top of the window the description of the current location: the user sees that he is in Auberge Guest Room with a person called Helmut von Schneider and that there are different exits. Then the user typed the command ‘who’ and to know information about his/her partner: connection and idle time as well as location in the MOO world. Finally at the bottom, one can see that the partner called Sherlock sent a message, his location (‘Mystery House’) is embedded in the message.

All actions in the MOO and in the whiteboard were recorded. The subjects were provided with a map of the inn (see figure 3) printed on a paper sheet. It must be emphasized that the solution to the problem was not intrinsically spatial (i.e. it did not require inferences such as "Helmut cannot go from the bar to his room at 9PM without meeting Hans who left the bar at the same time, hence he lies.")

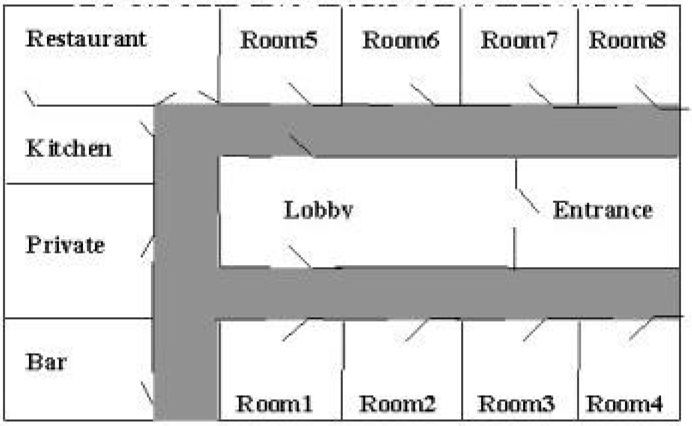


Figure 3: The map of the "Auberge du Bout de Nappe", the space that subjects had to explore to ask questions to suspects and inspect interesting objects.

We ran the experiments with 18 pairs (Dillenbourg & Traum, 1997). The two subjects were located in two different physical rooms, communicating and performing the task through the MOO. Subjects were at different levels of MOO experience, ranging from novices to experts. They were not used to working together. We did not control the degree of knowledge of the partner nor the gender. The average time to identify the murderer was two hours. The system automatically records all actions and interactions in the MOO and in the whiteboard[2]. We present here only some results, which are relevant with respect to spatial aspects.

Space modifies communication patterns

We coded all protocols and counted the rate of acknowledgment as the percentage of utterances being answered by the partner. Acknowledgment went from elementary back-channel messages (such as "uh huh") up to elaborated answers, rephrasing, counter-arguments, and so forth. The average rate of acknowledgment across all situations was 41%. We studied how this rate varied according to the spatial positions (same room or not). When the subjects were in the same room, they acknowledged on average 50 % of utterances versus only 34% when in different rooms ($F(18,1)=9.75$, $p< .05$). This is consistent with Cherny's findings (1995): she observed that back channels are significantly absent from long distance conversation (moo command “page”) versus co-present interactions (moo command “say”). The

---

[2] Complete protocols from MOO dialogues and the content of whiteboards are available on the WWW http://tecfa.unige.ch/tecfa/tecfa-research/cscps/Experiments/key.html

command ‘say’ unlike ‘page’ is used to talk to a character located in the same room. The syntax is say <message>. The command ‘page’ is used to talk to a character that is in another room. The syntax is page <character name> <message>.

Moreover, this did not imply that subjects significantly met for acknowledgment; this would have been too expensive. However, it often occurred in these experiments that the detectives explicitly decided to meet in the same room when they had long discussions, especially at the end of the task when they had got all information and wanted to synthesize it. In table 1, Sherlock accepted (78.7) such a proposition and verified that they actually were together (79.1) before resuming discussion.

Time	**Location**	**Subject**	**Action**
76.9	Kitchen	Helmut	*say* so shall we meet to discuss our solutions?
78.6	Kitchen	Helmut	*Who*
78.7	room 5	Sherlock	*say* Yes, let meet in the bar
78.8	room 5	Sherlock	*Who*
78.8	room 5	Sherlock	*go* out
78.9	Kitchen	Helmut	*walk to* bar
78.9	UC	Sherlock	*go* LC
79	LC	Sherlock	*go* B
79.1	Bar	Sherlock	*Who*
79.2	Bar	Helmut	*say* ok, what's your guess?

Table 1: Subjects often meet for long discussions (from Pair 12). MOO commands are in italic. The *who* command lets users know what other players are logged on and what room they are in. The *go* and the *walk to* commands teleport the user to the room whose name he or she give.

We also observed that the delay of acknowledgment is shorter when subjects are in the same room. Independently from the use of 'say' or 'page', the subjects answered to each other after 39 seconds when they were in the same room versus 59 seconds when they were in different rooms (F=6.56, N = 18, df 1, p= .015). A shorter delay might indicate a greater attention from the subject who answered and/or a tendency to give shorter answers (the delay included the time necessary to type the answer because a message was processed only when the user hit the return key). This was however not the case: the average length of 'say' and 'page' messages was almost identical (respectively 46.8 and 48.8 characters per message). We might hence interpret shorter response delay as a sign of a greater attention from the subjects who were in the same room. Another interpretation is that the users’ location was related with the content of their interactions. In this study, the data (MOO objects) necessary to solve the problem were distributed in different rooms. Co-presence increased the probability that subjects were concerned with the same data (i.e. talked about things and hence acknowledged each other more frequently and more rapidly).

Spatial coordination

Given the salience of the spatial metaphor, we expected that the subjects would maintain knowledge about their respective positions. However, we did not observe many cases where the subjects explicitly interacted about their current position ("I am in lobby", "Where are you?",...) or used the command "who" (which indicates who is where). Our interpretation was not that the subjects did not know where their partner was, but rather that they maintained this knowledge without explicit acts. There were several ways in which the subject might know where his or her partner was:

- The Moo automatically provided information about mutual positions: every time a page was received, every time users met or separated, plus every time where one saw the consequence of an action being performed by one's partner, and so forth. It might be that the information so provided was sufficient for the task. The second study explores this hypothesis.
- The whiteboard indirectly provided information on the visited rooms. Most of the pairs put on the whiteboard a collection of small notes containing the information collected. This information was often structured by room, either implicitly or explicitly. It was hence straightforward to infer where one's partner was or had been. The partner's position could also be inferred from the information reported by the partner in MOO dialogues.
- Two pairs of subjects used the whiteboard more directly for maintaining mutual position. They both reproduced the provided auberge map on the screen. In one pair, the users pasted their initial ("S" for Sherlock, or "H", for Hercule) on the map and started to move it when they moved in the MOO. In this case, the cost of spatial coordination was very high, since subjects had to update the graph every time they moved. Position information did not remain true long enough to be advantageously displayed manually on a persistent medium. Each subject might doubt whether his partner has updated his position or not on the graph. This approach was only viable if it would be carried out automatically by the system.
- In another pair, the subjects pasted a "done" label on each visited room.

We also observed that subjects often talked about future positions ("I am going to the restaurant", "Where are you going?",…). These utterances contributed to spatial coordination, although a detective could never be sure whether his partner would actually go to the agreed location nor how long (s) he would stay there. These utterances fulfilled a more important function with respect to the problem solving strategy. Since information was distributed over the virtual space (suspects and objects were in different rooms), negotiating where to go next was a concrete way of discussing how to solve the problem.

Moreover, we found that space supported implicit coordination. The user path indeed reflected his or her strategy (at least if it seemed to follow a direction) and one partner might anticipate the other’s intentions by tracing his or her spatial path (if the user knows that the upper corridor has 4 aligned rooms and that his partner has visited the three first ones, he will certainly expect the partner to visit the fourth room). Each partner could observe where the other goes without asking him explicitly.

Space is the main criterion for division of labor

The last insight about spatiality this experiment gave us concerns the way participants used space to organize the division of roles/labor among them. Collaborative processes often include co-operative phases, i.e. phases with a systematic division of labor (Dillenbourg, and al 1997), and *space was the main criterion for division of labor*. The subjects had to collect information from 12 suspects located in different rooms. There were different ways of dividing the work among the pair: each individual could care about one suspect or each individual could explore a limited portion of space. One of the most striking features in this experiment is that all of the 20 pairs coordinated their work on a spatial basis (e.g. one explores the rooms in the upper corridor and the other in the lower corridor). Two pairs used also another criteria (staff versus guests, males versus females) but only for a short period of time. These results mean that space offered a very familiar and natural resource to coordinate.

Moreover, partners could express (dis)agreement by performing actions or movements. For instance, sometimes, one user might have suggested to the other that he or she should ask some questions to a suspect, and the second user did not answer by words but simply moved to this suspect's room thereby acknowledging his or her partner’s suggestion. Or, conversely, he or she might have expressed disagreement by going to another room. This form of negotiation by action (a sort of speech acts in reverse) applied also to various other MOO commands, not only those relating to spatial positions.

Space supports grounding and building shared knowledge

Co-presence created a *micro-context* which supported verbal negotiation. In this study, when the users met, they expected their partner to say something about the suspects or the objects present in that room. This micro-context helps to establish mutual understanding, namely to solve references in the use of pronouns. For instance, in one observed pair, both users were in the kitchen. The two users met in a virtual room and one said “He lies” to his partner and “he” has not been grounded in a previous utterance. However, as the two participants were in a virtual room in which only one suspect was located, each subject may assume that “he” was this suspect. In other words, the context had hence been narrowed down by the spatial architecture; the scope for misunderstanding would have been broader if several suspects were in a unique room.

Mutual understanding was also improved by knowing where one's partner has been. For instance, if Hercule knew that Sherlock had gone to room 5 and that Hans (a suspect) was located in room 5, then Hercule might infer that Sherlock had *probably* collected information from Hans. This was due to the fact that there was an almost one-to-one relationship between knowledge sources (suspects and objects to be looked at) and rooms. The virtual space helped to *know what one’s partner knows*, a first step in building a shared understanding of the task (Clark & Brennan, 1991; Dillenbourg & Traum, 1997). We focus on the topic of mutual understanding and mutual expectations in the fourth study.

To conclude, on the one hand we have found that participants take space into account since it has a functional influence on the users’ behavior when communicating (rate and delay of acknowledgement). On the other hand, people seemed to perform very few acts of spatial coordination. This must be explained by the fact that participants were provided with multiple spatial coordination cues: the whiteboard, dialogues (“I am going to see Helmut”), affordances of places, the paths taken by the partner, MOO implicit acts ("You sense that X is looking for you in room Y", it means that Y received a page from his partner who is in room Y), MOO explicit acts (The command ‘who’ lets you know what other players are logged on and what room they are in). In addition, because of the close *relationship between the virtual space and the problem space*, the users might interpret mutual positions, movements and actions in virtual space in order to build mutual knowledge regarding the problem state, the problem strategy or simply what the other meant.

After observing the spatial behaviors in this study, we designed a second study in order to observe specifically the mechanisms of spatial coordination in a context in which it was more important to task success to coordinate on awareness of mutual position. The next experiment hence focuses on one specific act of spatial coordination, which is MOO implicit acts.

Second study: Triviaworld

This second study was specifically designed to investigate spatial coordination (Montandon, 1996), still in a MOO environment. It investigates why in the previous study the subjects did not perform many explicit acts of spatial coordination (hereafter EASC). As mentioned in the previous section, our interpretation was that:

1. Messages automatically generated by the MOO system conveyed enough spatial information for the task to be solved;
2. Information about mutual position could be inferred from other sources of information displayed on the whiteboard;
3. The task did not require a fine spatial coordination. Spatial mis-coordination would only generate minor loss of efficiency, namely failed communication (using "say" while the partner is not in the same room) and sub-optimal data collection strategies (two partners visiting the same rooms).

In this second study, we controlled factors 2 and 3, and tested the validity of 1. This first explanation was most interesting because it can be generalized to other virtual environments, since they generally include the same type of messages. Hence, our main hypothesis was: if one suppressed these side-messages, subjects would perform more EASCs.

Experimental setting

In order to control the second factor (the role of the whiteboard), we chose a standard MOO client, without a whiteboard. Besides this, the experiments were run within the same MOO environment as in the previous study. To control the third factor, we selected a task, which implied a finer spatial coordination than in the previous experiment. In this study, the need for spatial coordination was created by a simple rule; subjects are not allowed to meet. The task consisted of finding four letters, which constituted a word. Each letter was obtained by answering (trivia) questions on information technology. Each question was located in a room. For each question, a clue was available in another room. The subjects had to explore the rooms to get the questions and, if necessary, the dues. The key rule was that subjects were not allowed to be in the same room. If they met they were each sent to a labyrinth and lost precious time while escaping from it. The maximum time allowed is twenty minutes. The number of rooms was relatively low; hence the probability to meet accidentally was high.

The experiment included two tasks based on the same principle and on the same topology of rooms. Only the content and location of questions and clues differed. The tasks were assigned two conditions. In the "rich" condition, the subjects used a standard MOO. In the "poor" condition they used a modified MOO environment in which the spatial messages automatically provided by the system have been suppressed. Actually, the rich condition was not very rich: since subjects avoided meeting, they did not receive the spatial information provided by the MOO when two users arrived in the same room or when one left. The richness would only be related to the side-message, which came with every 'page' communication. Moreover, the 'poor' condition was not extremely poor, since it still included the 'who' command. The contrast between the two conditions was hence moderate.

The experiment was run with 20 pairs. The two participants were located in two different physical rooms. Each pair passed through the two conditions. In order to counterbalance the order effect, 10 pairs did task 1 in the rich condition and then task 2 in the poor condition, while the 10 other pairs did task 1 in the poor condition and then task 2 in the rich condition (the balancing hence concerning the condition and not the tasks, considered as equivalent). The subjects were familiar with the MOO. Some of them did it from a machine in our lab, while others were connected from in the world, via the Internet. A few subjects in remote places stopped in the middle of the experiment, without giving any explanation. They were not counted here.

Of the 20 pairs, 4 found the solution to both tasks, 8 solved only one task. Among the 8 pairs, which did not solve either problem, 4 were close to the goal (3 letters identified out of 4), while 4 pairs were far from the solution. Six pairs never went to the labyrinth (i.e. they were hence well coordinated), 10 went once, the remaining ones went between 2 and 6 times. On average they spent 37 minutes for the whole experiment.

Results

We counted three types of explicit acts of spatial coordination:

- Type 1: EASC-current: Communication regarding the current position (e.g. “I am in blue room” or “where are you?”)
- Type 2: EASC-future: Communication regarding a future position (e.g. “I go to blue room” or “where do you go?”)
- Type 3: EASC-who: Using the ‘who’ command (which indicates who is where).

The third category differed from the previous ones with respect to the mutuality of knowledge. If Heidi paged "I am in the lobby", Kaspar knew where she was, but in addition Heidi knew that Kaspar probably knew where she was. If Heidi used "who", she knew where Kaspar was, but Kaspar remained ignorant that she had verified his position. A type-1 or type-2 question followed by an answer was counted as one EASC. Table 2 gives the results.

Number of EASC per minute	**Condition "rich"**	**Condition "poor"**
EASC-current	mean = 0.08, SD = 0.09	mean = 0.17, SD = 2.9
EASC-future	mean = 0.17, SD = 0.16	mean = 0.2, SD = 0.18
EASC-who	mean = 0.30, SD =0.31	mean = 0.34, SD = 0.35

Table 2: Comparison of EASC per minute in the two conditions

Since subjects spent significantly more time in the rich condition than in the poor condition, we counted the number of EASC per minute. Given the high variance of these data, the following results are presented with caution. As expected by our hypothesis, the number of EASC-current was significantly higher in the 'poor' condition than in the 'rich condition' (T(19)= 3.28, p< .05). The number of EASC-future was also higher in the 'poor' condition, but the difference was not significant. The fact that our hypothesis was confirmed for EASC-current and not for EACS-future was logical: the side-messages provided by the MOO convey information regarding current position but did not inform about future position. The number of EASC-who was slightly higher in the poor condition than in the rich condition, but the difference was not significant. If we did not take the time into account, subjects even performed slightly fewer "who" commands in the poor condition. There was some redundancy between EASC-current and EASC-who, which might explain that those who perform more EASC-current did not need more EASC-who.

On average, the pairs performed more EASC in the second task (T(19)=2.29, p<.05). Moreover, we observed an interaction between the order effect and the condition effect. The rich/poor difference was more important for the second task than for the first task. The pairs that passed from the poor to the rich condition continued to produce EASC, since they learned that it was important. Hence, the number of EASCs did not decrease in the second task. At the opposite, the pairs that passed from the rich to the poor condition were used to receive spatial information from the MOO and hence performed many EASCs when this information was suppressed.

Surprisingly, the pairs that produced more EASCs were not more effective in avoiding meetings (i.e. not more effective in spatial coordination). Some pairs did not coordinate action; they simply took risks. Other pairs established from the beginning a distribution of rooms into territories in such a way that they should never meet (8 pairs did it for the first task, 4 for the second – 3 of them using territories for both tasks).

The conclusion that should be drawn from this experiment is that space was meaningful for users because they performed lots of explicit acts of spatial coordination when they were not provided with a spatial awareness. The next study examines the effect of a location-awareness tool as well as focus on a result drawn from the first experiment: the fact that spatiality could support the grounding process by narrowing down the context.

Third study: Proxima

In the first experiment, we observed an interesting functional role of space. The room that also includes one agent or key object seemed to be used by subjects as the by-default context to disambiguate utterances. A MOO virtual room could thus narrow down the conversational context by providing specific cues. This observation may develop our functional understanding of virtual space: we hypothesized that *spatial awareness supports grounding by providing subjects with the contextual cues necessary to refer to objects*. This hypothesis was hence related to the field of referential communication we presented in the literature review. The preliminary observations were bound to the room paradigm of MUD environments, which define discrete space (i.e. made up of rooms). This third study was conducted in a continuous space where rooms do not simply define in/out relations but where distance matters. The MOO conversational rule “I don’t need to make explicit what I refer to if it’s the same virtual room” would in a 3D virtual space become something like “I don’t need to make explicit what I refer to if it’s close to me in virtual space”. We thus chose another type of collaborative virtual environment to check if the results obtained in MOO still hold and to investigate further issues. In a 3D environment, space is graphically represented, instead of the verbal description of MOOs.

Experimental setting

We used an experimental 3D Virtual Environment developed in VRML where two subjects (N=20 pairs) are required to collaborate to solve a simple object-matching task. The subjects were seated in different rooms and could only interact with their partner through the VE. The environment constructed for the experiment was figurative and poor in details as shown on figure 4. The task (10 randomized rounds) was for both subjects to locate a target object from amongst nine objects located in the VE to communicate their (the emitter's) finding to the partner using a structured communication interface and then for the partner (the receiver) to confirm or reject the proposition.

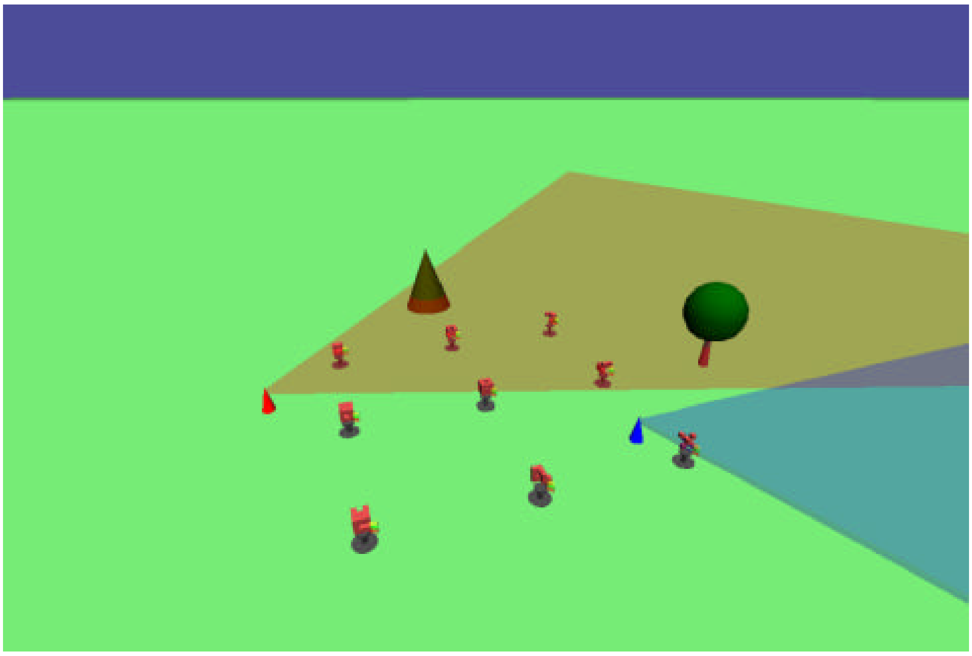
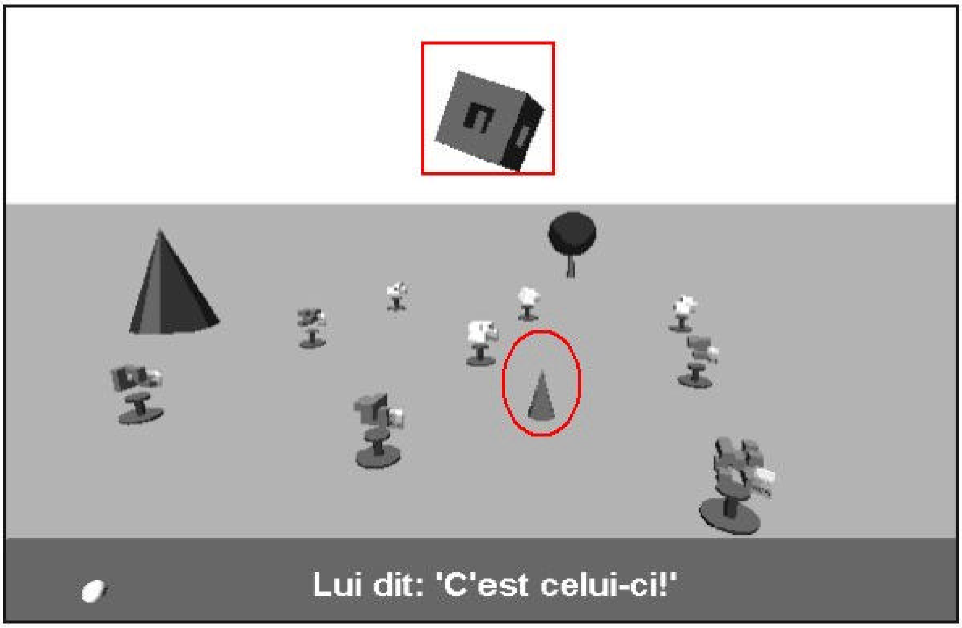


Figure 4: Aerial view of the virtual environment that gives a global picture of the VRML world. This view is not shown to the players. We see here avatars located at different point target object from amongst nine objects.

During the task the target object was always shown in the upper portion of the window as shown in figure 5. All of the nine objects were cuboids and highly similar to each other; therefore the object-target matching task was far from straightforward. A quick glance at objects in the VE was insufficient to ascertain a match with the target object; subjects rather had to take time to explore the objects in detail (i.e. by approaching the object and turning). The representations of the subjects in the virtual space (i.e. their avatar) were simple red cones. In addition, there was no deictic in this environment: the only way for a player to figure out which object the partner referred to is to interpret the partner's distance from objects, the partners movement direction and (in the awareness condition) the partner's gaze direction.



Lui dit: 'C'est celui-ci!'

Figure 5: My nose-less partner (the cone circled) tells me that he found the target object (in a square). My only way to figure out which object he refers to is to interpret his distance from objects, his movement direction and (in the awareness condition) his gaze direction.

The use of simple upright cones, as avatars, was a crucial experimental choice, as this representation carries no information on the orientation of the avatar. Therefore, there was no way for a user to tell the field of view of the partner on the VE. We provided the users with a gaze awareness tool: every object in the field of view of the partner's avatar was highlighted using a different color to those objects out of their field of view. The presence or absence of this awareness tool constituted the experimental condition of the study. Position and orientation of the avatars in the VE were logged every second. Avatar actions, such as the manipulation of objects or communication using the structured interface, were also logged. From these raw data we measured distance between the emitter and the reference object and an ambiguity measure consisting of the sum of examined objects by the receiver prior to he gave his or her answer (i.e. the greater the number of manipulated objects the greater the ambiguity of the situation). We used a 2x2 experimental plan in which each pair passed 5 sequences of one condition (with the awareness tool or not) and then 5 sequences of the other condition.

Hypotheses

We postulated the following hypotheses:

- Hypothesis 1: The proximity of the emitter to the referred object clarifies the referential context for the receiver.

- Hypothesis 2: The awareness tool clarifies the referential context. Users consult fewer objects when they are provided with the awareness tool.
- Hypothesis 3: The distance from the emitter to the referred object should increase with the presence of the 'awareness tool'. According to (Clark and Wilkes-Gibbs, 1986) least collaborative effort principle, conversing partners tend to minimize their collaborative effort. The redundancy of context disambiguating clues (i.e. proximity and view awareness) should lead to a slackening of the collaborative effort when possible, that is the proximity to the object. In conditions with the awareness tool the emitter will tend to be more distant from the referenced object.

Results

Distance between the emitter (when emitting) and the consulted objects was positively correlated to the number of different objects consulted before answering (Pearson's bivariate correlation: .206 significant at the 0.01 level). Though the correlation was relatively small, this distance measure was highly significant. Thus, we considered hypothesis 1 to be confirmed. This must be because of the moment of the interaction. As a matter of fact, when the emitter pushed the button to propose the object to his or her partner, this partner then tried to localize the emitter in order to find the referenced object. For the partner, the closest object of the emitter was certainly the referenced object. Therefore, the smaller the distance between the emitter and the object he is referring to, the faster the receiver finds this object. This is the most important result of this study.

With regard to the second hypothesis, we didn't observe any difference between sequences with or without the awareness tool (p=.983). There were no significant differences between the number of objects consulted before answering with or without the awareness tool. Therefore, the second hypothesis was invalidated. However, this result should be explained by the order the pairs passed the two conditions. Half of the pair indeed began with the awareness tool (order: with → without) whereas the other half began without (order: without → with). Participants hence played with both interfaces. When participants firstly used the interface with awareness tool, the number of objects they consulted was lower. An ANOVA test on the first five sequences showed a trend of effect of the awareness tool on the number of consulted objects (F(1,97)=3.652, p=.059). Besides, when the awareness tool was suppressed in the second interface (i.e. for the group 'with→without'), the number of consulted objects increased a little; this result was consistent with the second hypothesis, suppressing the awareness tools made context clarification more difficult. Nevertheless, for the second group (‘without→with’), there was also a little increase of the number of consulted objects. Those results were unfortunately not significant.

Finally, although different distance measures to the referred object tended to be greater in the condition with the awareness tool, an ANOVA revealed no significant interaction between view awareness and proximity.

In conclusion, this experiment revealed that users might use some features of virtual space, namely distance, to support a core mechanism in collaboration, defining the referential context. It still remained an open issue for us to dissociate to which extent the emitter’s move to the object was due to the task constraints or reflected a deliberate deictic move. It only indicated that, when the emitter had to perform this move for task-specific constraints, then the receiver was able to interpret distance and movements to disambiguate references. This information might however be used by CSCW designers for instance to decide how they position objects in virtual space.

Fourth study: Spaceminers

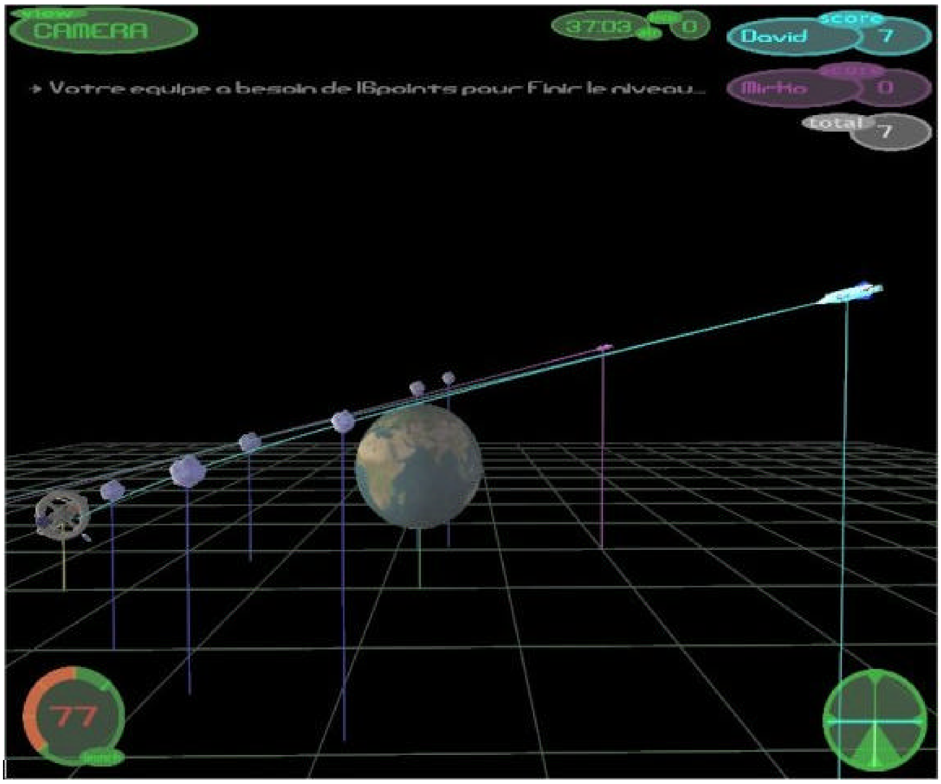
After having focused on the very topic of awareness in the second study and on referential context in the third study, this last experiment deals with the effect of location awareness on a specific collaborative process: mutual modeling. This process refers to the inference an individual makes about his partner’s knowledge, strategies and belief when collaborating.

In order to reach that goal, a computer game, Spaceminers[3], was employed to conduct experiments. This game engaged players in a 3D virtual environment, which is a continuous space, as in the previous experiment. In this game, two players located in different physical rooms are involved in a space mission. They communicated via a headset. Experimental subjects consisted of 18 pairs of males (N=18). Participants were assigned a partner with whom they were not familiar. The purpose of this game was to collect the largest amount of minerals located in asteroids and to bring them to a space station in a 3D space. The score represented the number of collected minerals docked to the space stations launched by the two players. The score was influenced by several factors such as: the drone trajectory, the launch speed, the tools positions (that influenced the drone trajectory), the number of

---

[3] Developed at the Geneva Interaction Lab (University of Geneva) by Yvan Bourquin, Jeremy Goslin and Thomas Wehrle

asteroids in the environment and the planet positions (that modified the gravity). Figure 6 depicts Spaceminers interface.



→ Votre equipe a besoin de 18points pour Finir le niveau...

Figure 6: The game environment made up of a planet (at the center of the picture), asteroids (on the left of the planet), two spaceships (on the right) and a space station (on the left). This kind of view can be seen in the scout mode. The individual scores (for David and Mirko) as well as the group score are located in the upper right-hand corner. The timer and the current game level are just on the left of the score on the top. In the lower left-hand corner is located the launch speed. One can see the compass in the lower right-hand corner. This screenshot depicts the scout view (since we see the spaceship) as indicated in the upper left-hand corner. David (the player who controls the ship) manages to collect asteroids and to dock his drone to the space station. Thus he wins 7 points.

The users could play in two modes that correspond to two viewpoints: the explorer mode and the camera mode. They could switch from one mode to another by pressing a key on the joystick. In the explorer mode, the position of the spaceship was fixed and players launched drones that passed through as many asteroids as possible on their way to the space station. Once the drones were launched players had no control over them. It depended only on the direction of the explorer and the launch speed of the drone controlled by the player and on the gravity of planets. In the camera mode, players could move their camera around in space by moving the joystick. The camera was very useful to see space from another viewpoint and to place artifacts in space.

The Awareness tool (AT hereafter) was the view of the partner's camera and his laser pointer. By seeing the camera of his partner the player could obtain awareness information about his team-mate's location and gaze, as shown on figure 7. Thus he could help him to drop artifacts into space or to adjust his trajectory. Those artifacts were meant to foster collaboration between players. The presence or absence of this awareness tool constituted the experimental condition of the study.

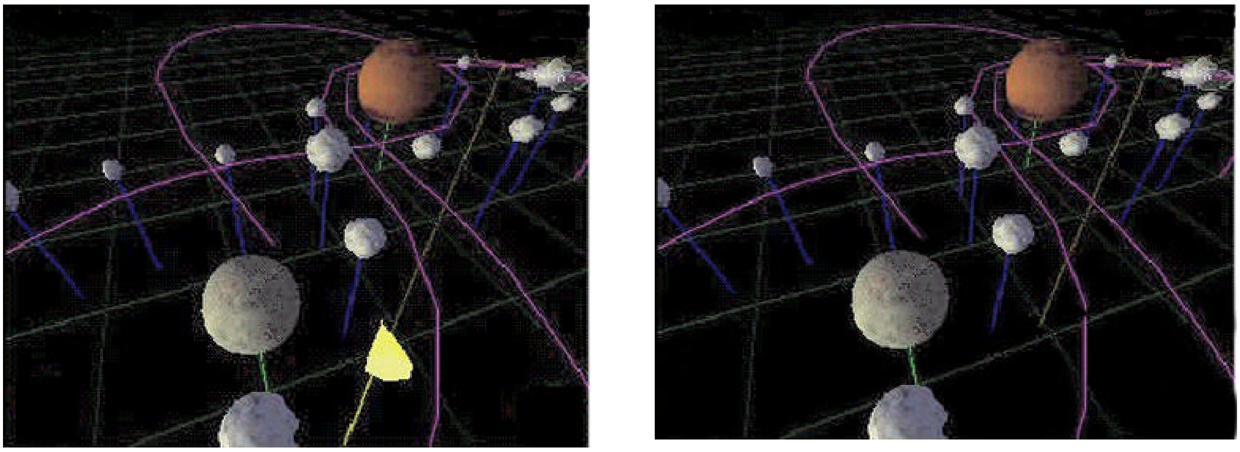


Figure 7:. Presence (figure on the left) or absence of the awareness tool (figure on the right). The view of the scout, represented by a polygon, is basically the awareness tool. This view can only be seen in the explorer mode (from the spaceship). Thanks to this awareness tool, the player can a) know where his partner is and also where he is pointing by seeing the direction of the cone.

Experiments lasted approximately 2 hours and were conducted in French. After a tutorial, players had to complete three levels. The task performance was the sum of player A's score and player B's score. Mutual Modeling (MM) is measured by two different questionnaires. First, during the game and for each of the three levels, players had to answer to two multiple-choice questionnaires. Those questionnaires asked them about what they were intending to do at the moment (guiding his partner, trying to understand his strategy, trying to establish a common strategy, adjusting a shoot, etc.). Then, the questionnaires asked each player about what he thinks his partner was currently doing (same propositions as the previous questionnaire). We compared the first answer of a player (about what A declared he was intending to do) to the answer of his partner to the second question (about what B believed A was doing). Consequently, our evaluation of the MM accuracy was the number of common answers to those two questions. We compared whether A's prediction of B's answer matched with B's actual answer.

We postulated two hypotheses:

- Hypothesis H1: Pairs with awareness tools are more effective (i.e. higher team score) than pairs without awareness tools.

- Hypothesis H2: Pairs with awareness tools build more accurate model than pairs without awareness tools. *The global mutual modeling evaluation (MM) should be higher when the players have an awareness tool*. The MM is the sum of the objective evaluations of the mutual modeling of a team during the whole game, measured by the in-game questionnaires.

The first hypothesis was confirmed; pairs with AT reached higher scores than the others (F = 4.84, p = 0.043). The mean score for pairs with AT was 258.67 (SD = 90.80) and 175.67 (SD = 67.48) for pairs without AT. Besides, no pairs without AT reached the mean score of the pairs with AT.

The second hypothesis was not validated; players with awareness tool did not have more accurate mutual modeling. Despite 1.63 for pairs with the tool and 1.58 for the pairs without (F = 0.02, p = .889), the standard deviation was 0.48 for pairs with AT and 0.87 for pairs without. It went against our hypothesis and the ANOVA test shows that H2 is invalidated. The use of the awareness tool did not improve the accuracy of the mutual modeling. The representation of one's partner strategy was not facilitated by the information conveyed by the awareness tool. Those results lead us to three possible conclusions. First, the awareness tool, by showing information about the partner's locations and gaze, did not improve the accuracy of the mutual modeling. Second, the game did not require participants to maintain accurate mutual models; they did not have to care much about each other. And finally, our evaluation of mutual modeling was not very accurate.

Nevertheless, we also focused on behavioral data, which was stored in the log-files. We looked specifically at the percentage of time spent in each view (camera or spaceship) by the pairs and we noticed an interesting difference. A two-way analysis of variance showed that pairs in the awareness condition who spent more time in the camera mode reached higher levels of mutual modeling (*F* = 8.02, p = 0.015) than the others. That means that the teams who effectively used the awareness tools reached higher levels of mutual modeling. It implies that there was an effect of the awareness tool on mutual modeling only for the teams who used the awareness tool. Awareness information could help players in order to estimate their partner's strategies if the participants understood that they have to make an effort: spend an accurate time in the camera view. Teams who did not spend enough time in the camera view had no benefit of the awareness tool. Our finding raises a new question: did players really use the awareness tool? Indeed, if there was an effect of the tool on mutual modeling only for the players who used it frequently, it might be possible that only a few players in the tool condition noticed the advantage of using it.

The fact that teams in the awareness tool condition reached higher scores than the others is consistent with the findings of Gutwin et al. (1996) and Espinosa et al. (2000). In fact, this tool provided a continuous feedback to the partner who could see where was his team-mate. This could be extremely useful in tasks like object positioning. In such tasks, player A guided player B's movement by giving him instructions about where to drop the object. Additionally, the AT provided visual evidence about the player's location. The team was thus more effective because player A had not to verbally describe where he was and player B had not to interpret this description. As suggested by Gutwin et al. (1996), the use of the awareness tool transforms the task from a verbal to a visual activity. Besides this finding is consistent with Hindmarsh's study (Hindmarsh et al., 1998): it's difficult for users to establish mutual orientations in virtual space b since there is a lack of a common frame of reference. Where Hindmarsh et al. suggest a 2D map to alleviate this, we think that players could also benefit from the awareness tool to create such a common frame.

However, those results call for certain restrictions. On the one hand, the number of participants was quite low: eighteen pairs (nine in each conditions). On the other hand, we can also have reservations about the instrument. Spaceminers was perhaps too complex and suffered from usability troubles that were difficult to deal with for lots of people. Furthermore, the method used to measure the accuracy of the mutual modeling may be unsuitable. Using a simple questionnaire to measure the accuracy in predicting partners' answers is far too subjective. We should use a more objective method to evaluate this variable. A solution would be to analyze the redundancy (i.e. the number of times player A performs an action that player B has previously performed). Or we should have compared what B thought A has done and what A has really done.

Concerning this last experiment, the conclusion is that being aware of the partner's location improves the performance but does not necessarily contribute to the construction of a mental model of one's partner.

General discussion

This paper is about how people rely on spatiality for collaborative problem solving. The four experiments show that being aware of the partner's position in space impacts collaborative processes, namely division of labor, grounding, performance and communication. The first study reveals that users modify their communication behavior when they meet their partner in a virtual room: they change acknowledge more often and more quickly their partner's message. However, despite this sensitivity to virtual co-presence, subjects do not often explicitly coordinate their movements. The second study indicates that the rarity of explicit acts of spatial coordination is (at least partly) explained by the fact that the MOO automatically provides awareness information about space through side-messages. The third study showed that virtual space narrows down the conversational context: proximity between an individual and an artifact eases referential communication. Thanks to the fourth study, we found that knowing the other's position improves performance and could have peculiar impacts on the way people infer the other's intentions.

With respect to the framework presented at the beginning of this paper, we brought into prominence some of the social and cognitive roles of space that occurred in both kind of environment the physical world and virtual environments. Our results indeed show that virtual space also supports some of the functions afforded by real space. Among all the functions of space presented in the literature review, we especially addressed here the person/artifacts relationships and how space affords activities. Both of these core components of collaboration can be found in virtual space. For instance, we saw that referential communication (Krauss and Weinheimer, 1966, Clark and Wilkes-Gibbs, 1986) is afforded by proximity in the third experiment. In experiment 1 and 2, we saw that partitioning activities (Harrison and Dourish, 1996) and dividing labor is supported by spatiality in virtual space as in physical settings. Like Benford et al. (1993), we found that portion of virtual space could define a particular domain of interaction (Benford et al. 1993), especially through the use of different communication patterns. The fourth experiment also shown that mutual knowledge can be derived from spatial awareness like in physical space (Schober, 1993): knowing where is the partner allows to identify his/her point of view.

Table 3 summarizes the results drawn from the experiment with regard to the type of environment used (MOO and 3D continuous space). As can be noted, one can see that spatial awareness supports various processes in both kinds of environments. The point here was neither to compare environments nor to investigate which features of each environment lead to the results, but rather to verify if some results obtained in discrete textual space could be found in 3d continuous space.

Roles of spatial awareness	**Environment**	
	Moo	**3D space**
	Textual depiction of space, discrete, textual communication, textual commands to manipulate artifacts	**Graphical depiction of space continuous, audio communication, direct interaction to manipulate artifacts**
Improve task performance	x	x
Improve coordination	x	x
Support division of labor	x	not tested
Support communication	x	not tested
Support grounding	x	x
Support mutual modeling	not tested	x

Table 3: summary of the results obtained in the two kinds of environments.

Even though the experiments involved a low number of participants and different virtual environments (discrete space in MOO and continuous space in 3D graphical games), there were constant patterns like the fact that we always used distant pairs and obtained similar results in both kinds of environments (see table 3 for a summary). For instance, we noticed the same effect of space concerning grounding (how space narrows down the context) in both text-based and graphical environment. The point was not to compare the specificity of various environments but rather to verify if some results found on MOOs in an exploratory study still held in 3D collaborative virtual environment. The move from MOOs to 3D space is due to the fact that we wanted to see if results held when we changed a textual discrete space in a graphical and continuous space. Another methodological critique that could be made concerns the very concept of awareness tool as tested in experiments 2, 3 and 4. Actually, we considered here the awareness as a tool that conveys specific information about the participants' behavior. In fact, awareness is not only this kind of "widget"; the situation is more intricate. We should reconsider the definition of awareness as a diffuse flow of information (Mastrogiacomo, 2002): lots of different cues, signs, evidences which are combined. This flow makes sense and it is very difficult to create a tool to enable this combination. Of course, the design of the awareness tool might affect the experiments. We tested three types of awareness tool: the automatic AT in the MOO the gaze awareness and the location awareness in Spaceminers. In each case, the effects depend on the specific design features of the AT. Here we focused on synchronous awareness; results might have been different if the awareness tools were asynchronous. We are working on further investigations to address this issue. Another critic would also be that we tested awareness tools with pairs; in the context of multi-user environments with 4 to 50 users, things should change; paying attention to awareness cues left by 50 users is different. These cues are more disruptive but much more needed.

Moreover, these studies only cover one aspect of space, the social space, and ignore more intrinsically spatial aspects, which imply the users mental imagery. Within the social aspects of space, we only consider the perception and effect of co-presence. Other social space phenomena could be observed in more ecological experimental settings, involving many users with various tasks, such as the emergence of group territories (for instance in the first experiment, we noticed some occasional assignment of territory to individuals), the difference of behavior between rooms and so forth.

These studies draw several implications, for designing CSCW environments and proper awareness tools.

Our principle "*Design for Grounding*" refers to exploiting the topological properties of space when designing virtual environments as advocated by Harrison and Dourish (1996). We refine their idea by stating that people could use space topology (i.e. the connecting rooms, the position of exits, the artifacts available…) may facilitate the construction of a shared understanding of the situation. The designer's aim is to discover and come up with meaningful ways of making things perceptible for users. By putting an emphasis on specific spatial feature, designers can ease the achievement of the task. For instance, in the first experiment (Bootnap), if all the suspects were in the same room, space would fail to facilitate coordination. It is the fact that the suspects were located in different rooms that allowed the participants to establish a relationship between the virtual space and the problem solving space (if my partner is in room X he is collecting information about Y). What matters is not the properties of space *per se* but rather the topology and the content. For example, in the first experiment, player A knew that the upper corridor has 4 aligned rooms and that his partner has visited the three first ones, that is why he expected the partner to visit the fourth room. This information was useful for dividing roles among a group. Designing space in order to support grounding is not just a matter of re-creating 'virtual places' that gives feeling of presence, simultaneity of beings or allowing people to do something together with dedicated tools. It is rather giving users the opportunity to perform their task in an appropriate environment that supports their collaborative processes. One of the most important things here is to understand that the task and the environment that should support it are intricately related.

Therefore when designing a multi-user environment, one must address three questions:

- What are the kinds of social interactions that are required for the joint task? What are the forms of interactions between participants that could ease the task?
- What are the topological properties of space that ease those interactions? For instance: which artifacts are useful, where are they located and how users could interact with them in order to achieve the completion of the task.
- How can we design space with those constraints?

Finally, concerning awareness, the findings provide evidence that location awareness could enhance task performance if they provide a good way to support referential communication among teammates. A condition for this is that the AT is properly matched to the task. The tool should indeed make sense in the context of the task performed; for instance there should be objects or artifacts to describe and for which the awareness tool allow to reference. Moreover, the use of the awareness tool in the last experiment leads to transform a task from a verbal to a visual activity and hence induce a quicker completion of the task. Instead of letting participants describe their locations or the artifacts they are talking about, an awareness tool facilitate such referential mechanisms. Another interesting lesson is that subjects did not systematically use awareness tools. As we have seen in experiment 4, several participants did not really notice the potential of this tool. Thus, designers should not taken for granted that users will systematically employ an AT simply because it is available. They should teach them or make explicit their added value for the task. In addition, apart from the effectiveness of the awareness tools, their effects on collaborative processes should be put forward. Indeed, even though the results of the fourth experiment just hold for people who used the tool, there seems to be an impact of location awareness on mutual modeling. In sum, spatial awareness increases mutuality of knowledge in purposely designed virtual space. From the partner’s position one can infer his/her activity. From the trace, the strategy might be inferred and the direction could reveal the goals. Of course this hold if the meaning and use of the tool is properly understood. The condition for this result is indeed that the users understand the added value of such a tool. Noticing the gain due to the awareness information is not obvious per se since the users have first to understand the task to be performed and which kind of tool could support a) the task performance and b) the collaboration. Therefore awareness tool design should take this into account through the clarification of how it is related to the task and the collaborative processes required to undertake it.

References

Benford, S. D., Bullock, A. N., Cook, N. L., Harvey, P., Ingram, R. J. and Lee, O. (1993): From Rooms to Cyberspace: Models of Interaction in Large Virtual Computer Spaces, *Interacting With Computers*, vol. 5, no. 2, pp.217-237.

Benford, S., Bowers, J., Fahlen, L., Greenhalgh, C., & Snowdon, D. (1995): User Embodiment in Collaborative Virtual Environments, *Proceedings of the 1995 ACM Conference on Human Factors in Computing Systems* (CHI'95), New York: ACM Press, pp. 242-249.

Biocca, F., Tang, A., Lamas, D., Gregg, J., Gai, P. & Brady, R. (2001): *How do users organize virtual tools around their body in immersive virtual and augmented reality environments?: An exploratory study of egocentric spatial mappings of virtual tools in the mobile infosphere*. East Lansing, MI: Media Interface and Network Design Lab.

Bowers, J., O' Brien, J., Pycock, J., (1996): Practically Accomplishing Immersion: Cooperation in and for Virtual Environments, In Q. Jones, and C. Halverson, (eds): *Proceedings of 1996 ACM Computer Supported Cooperative Work (CSCW 96)*, Boston, MA, New York: ACM Press,pp. 380-389.

Bradner, E. and Mark, G. (2002). Why Distance Matters: Effects on Cooperation, Persuasion and Deception. *Proceedings of the 2002 ACM Conference on CSCW* (CSCW'02), New Orleans, November 16-20, New York: ACM Press, pp. 226-235.

Bruckman, A and Resnick, M. (1995): Virtual Professional Community: Results from the MediaMOO project. *Convergence*, vol. 1, no 1.

Cherny, L. (1995): *The situated behavior of MUD back channels*. Internal Report. Stanford University, Linguistics Department.

Cheyne, J. A., & Efran, M.G. (1972): The effect of spatial and interpersonal variables on the invasion of group controlled territories. *Sociometry*, vol. 35, pp. 477-487.

Clark, H.H. and Brennan, S. (1991): Grounding in communication. In L. B. Resnick, J. Levine & S. D. Teasley (eds): *Perspectives on socially shared cognition*. Washington: APA Books, pp. 127-149.

Clark, H.H. and Wilkes-Gibbs, D. (1986): Referring as a collaborative process. *Cognition*, vol. 22, pp.1-39.

Dieberger, A. (1999): Social connotations of space in the design for virtual communities and social navigation. In A. Munro, K. Höök and D. Benyon (eds): *Social Navigation of Information Space*. London: Springer, pp.35-52.

Dillenbourg, P. & Traum D. (1997) *The role of a whiteboard in a distributed cognitive system*. Swiss workshop on collaborative and distributed systems. Lausanne, May 1st 1997.

Dourish, P. and Chalmers, M., (1994): *Running Out of Space: Models of Information Navigation*. *Proceedings of Human Computer Interaction (HCI'94)*, Glasgow. New York: ACM Press.

Edney, J.J. (1976): Human Territoriality. In Prohansky, H.M., Ittelson, W.H., & Rivlin, L.G. (eds): *Environmental psychology: People and their physical settings*. New York: Holt, Rinehart & Winston, pp. 189-205.

Espinosa, A., Cadiz, J., Rico-Gutierrez, L., Kraut, R., Scherlis, W. & Lautenbacher, G. (2000): Coming to the Wrong Decision Quickly: Why Awareness Tools Must be Matched with Appropriate Tasks. In *Proceedings of the Conference on Human factors in computing systems*, (CHI'2000). The Hague, Amsterdam ACM Press, pp. 392-399.

Fitzpatrick, G., Kaplan, S. M. and Mansfield, T. (1996): Physical spaces, virtual places and social worlds: A study of work in the virtual.. In Q. Jones, and C. Halverson, (eds): *Proceedings of the 1996 ACM CSCW'96*. Boston, MA, pp. 334-343.

Fraser, M., Benford, S., Hindmarsh, J., & Heath, C. (1999): Supporting awareness and interaction through collaborative virtual interfaces. In *Proceedings of User Interface Software (UIST99)*, New York: ACM, pp. 27.36.

Fraser, M., T. Glover, I. Vaghi, S. Benford, C. Greenhalgh, J. Hindmarsh and C. Heath (2000): Revealing the Realities of Collaborative Virtual Reality. Collaborative Virtual Environments. In *Proceedings of Collaborative Virtual Environments (CVE 2000)*, San Francisco, CA, New York: ACM, pp. 29-37.

Gattis, M. (1991): *Spatial Schemas and Abstract Thought*. Bradford Book: Cambridge, Massachusetts.

Greenberg S. and Roseman, M. (2003). Using a Room Metaphor to Ease Transitions in Groupware. In Ackerman, M., Pipek, V. & Wulf, V., (eds) *Beyond Knowledge Management: Sharing Expertise*, Cambridge, MA : MIT Press, pp. 203-256.

Gross, T. (2002): Virtual Communities on Stage: Supporting Chance Encounters, Communication and Awareness in a Theatre of Work. In Q. Jones, and C. Halverson, (eds): *Proceedings of the 2002 ACM Conference on Computer Supported Cooperative Work 2002* , USA, New Orleans, Nov. 16, 2002.

Gutwin, C., Roseman, M. & Greenberg, S. (1996): A usability study of awareness widgets in a shared workspace groupware system. In Q. Jones, and C. Halverson, (eds): *Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work (CSCW'96)*, Cambridge MA, New York: ACM Press, pp. 258-267.

Hall, E.T. (1966): *The Hidden Dimension: Man's Use of Space in Public and Private*. Garden City, N.Y.: Doubleday.

Halloran, J. , Fitzpatrick, G., Rogers, Y. and Marshall, P. (2004): Does it matter if you don't know who's talking? Multiplayer gaming with voiceover IP. In *Proceedings of the 2004 ACM Conference on Human factors in Computing Systems* (CHI 2004), Vienna, Austria, New York: ACM Press, pp. 1215 - 1218.

Hare, P. H., and Bales, R. F. (1963): Seating position and small group interaction. *Sociometry*, 26, pp. 480-486.

Harrison, S. and Dourish, P. (1996): Re-Place-ing Space: The Roles of Place and Space in Collaborative Systems. In Q. Jones, and C. Halverson, (eds): *Proceedings of the 1996 ACM Computer Supported Cooperative Work (CSCW 96)*, Cambridge MA, ACM Press, pp. 67-76.

Haynes, C. (1998): Help ! There's a MOO in This Class. In C. Haynes, and J.R. Holmevik, (eds): *High Wired: On the Design, Use, and Theory of Educational Moos*. Ann Arbor: The University of Michigan Press, pp. 161-176.

Henderson, D A and Card, S K (1986): Rooms: The Use of Multiple Virtual Workspaces to Reduce Space Contention in a Window-Based Graphical User Interface. *ACM Transactions on Graphics*, vol. 5 no.3, pp. 211-243.

Hindmarsh, J., Fraser, M., Heath, C., Benford, S., and Greenhalgh, C. (1998): Fragmented interaction: Establishing mutual orientation in virtual environments, In *Proceedings of the 1998 ACM Computer Supported Cooperative Work (CSCW 98)* , New York: ACM, pp. 217-226.

Jeffrey, P. and Mark, G. (1998): Constructing Social Spaces in Virtual Environments: A Study of Navigation and Interaction. In K. Höök, A. Munro, D. Benyon, (eds): *Workshop on Personalized and Social Navigation* *in Information Space*, March 16-17, 1998, Stockholm (SICS Technical Report T98:02) 1998) , Stockholm: Swedish Institute of Computer Science (SICS), pp. 24-38.

Joiner, D. (1976): Social Ritual and Architectural Space. In H.M. Prohansky, W.H. Ittelson, & L.G. Rivlin, (eds): *Environmental psychology: People and their physical settings*. New York: Holt, Rinehart & Winston.

Jul, S. and Furnas, G.W. (1997): Navigation in Electronic Worlds, *Sigchi Bulletin*, vol. 29, no. 4, A CHI 97 Workshop, pp. 44-49.

Kirsh, D. (1995): The Intelligent Use of Space. *Artificial Intelligence*, vol. 73, no. 1-2, pp. 31-68.

Knowles, E. S. (1973): Boundaries around group interaction: The effect of group size and member status on boundary permeability. *Journal of Personality and Social Psychology*, vol. 26, pp. 327-331.

Krauss, R. M. & Weinheimer, S. (1966): Concurrent feedback, confirmation, and the encoding of referents in verbal communication. *Journal of Personality and Social Psychology*, vol. 4, no.3, pp. 343-346.

Kraut, R. E., Fussell, S. R., Brennan, S. E., & Siegel, J. (2002): Understanding effects of proximity on collaboration: Implications for technologies to support remote collaborative work. In P. Hinds & S. Kiesler (eds): *Distributed Work*. Cambridge: MA: MIT Press, pp. 137-162.

Krikorian, D.H., Lee, J.S., Makana Chock T. and Harms, C. (2000): Isn't That Spatial?: Distance and Communication in a 2-D Virtual Environment. *Journal of Computer Mediated Communication*, vol. 5, no. 4.

Latané, B. (1981): The psychology of social impact. *American Psychologist*, vol. 36, no. 4, pp. 343-356.

Lombard, M and Ditton, F. (1997): At the Heart of It All:
The Concept of Presence. *Journal of Computer Mediated Communication*, vol. 3, no.2.

Lyman, S. & Scott, M.B. (1967): Territoriality. A Neglected Sociological Dimension. *Social problems*, 15, pp. 236-249.

Mastrogiacomo, S. (2002): Utilisation de Zones de Travail Partagées Asynchrones pour Améliorer la Comprehension Mutuelle dans les Groupes de Projets Distribués. Ph. D. dissertation, Dept. Informatique de Gestion. Ecole des HEC de l'Université de Lausanne.

Minami, H. and Tanaka. K. (1995): Social and Environmental Psychology: Transaction Between Physical Space and Group-Dynamic Processes. *Environment and Behavior*, vol. 27, no.1, pp. 43-55.

Montandon, L. (1996): Etude des mécanismes de coordination spatiale dans un environnement virtuel de collaboration. Mémoire de Diplôme d'Etudes Supérieures en Sciences et Technologies de l'Apprentissage. Non publié. TECFA, Faculté de Psychologie et des Sciences de l'Education, Université de Genève.

Moon, Y. (1998): The Effects of Distance in Local versus Remote Human-Computer Interaction. In *Proceedings of the 1998 ACM Conference on Human Factors in Computing Systems (CHI'98),* Los Angeles, CA, New York: ACM Press, pp. 103-108.

Moon, Y. (1999): The Effects of Physical Distance and Response Latency on Persuasion in Computer-Mediated Communication and Human-Computer Communication. *Journal of Experimental Psychology: Applied, vol.* 5, no. 4, pp. 379-392.

Munro, A.J., Höök, K. and Benyon, D. (1999): Footprints in the Snow. In A. Munro, K. Höök and D. Benyon (eds): *Social Navigation of Information Space*, pages 1-14. London: Springer.

Newlands, A., Anderson, A., Thomson, A., and Dickson N. (2002): Using Speech Related Gestures to Aid Referential Communication in Face-to-face and Computer-Supported Collaborative Work. In *Proceedings of the First congress of the International Society for Gesture Studies tool place* at the University of Texas at Austin, June 5 - 8, 2002.

Prohansky, H.M., Ittelson, W.H. & Rivlin, L.G. (1970): Freedom of choice in a physical setting. In H.M. Prohansky, W.H. Ittelson, & L.G. Rivlin, (eds): *Environmental psychology: People and their physical settings*. New York: Holt, Rinehart & Winston, pp. 177-181.

Rheingold, H. (2002): *Smart Mobs: The Next Social Revolution*. Cambridge: Perseus Publishing.

Rocco, Elena (1998): Trust Breaks Down in Electronic Contexts but Can Be Repaired by Some Initial Face-to-Face Contact. In *Proceedings of the 1998 ACM Conference on Human Factors in Computing Systems* (*CHI'98)*, Los Angeles CA, April 1998, New York: ACM Press, pp. 496-50.

Risden, K., Czerwinski, M.P., Munzner, T. and Cook, D. (2000): An initial examination of ease of use for 2D and 3D information visualizations of web content, International *Journal of Human-Computer Studies*, vol. 53, no. 5, pp. 695-714.

Schelling, T. (1960): *The Strategy of Conflict*. Cambridge: Harvard University Press.

Schober, M. F. (1993): Spatial perspective-taking in conversation. *Cognition*, vol. 47, pp.1-24.

Sorrows, M.E. and Hirtle, S.C. (1999): The Nature of Landmarks for Real and Electronic Spaces. In C. Freska, & D. Mark, (eds): *Spatial Information Theory, International Conference COSIT 1999*, Proceedings, Springer Verlag, Germany, pp. 37-50.

Stanton, N.A. (1994): Explorations in Hypertext: Spatial Metaphor Considered Harmful. *International Journal of Educational Technology*, vol. 31, no. 4, pp. 276-294.

Steinzor, B. (1950): The spatial factor in face to face discussion groups. *Journal of Abnormal and Social Psychology*, vol. 45, pp. 552-555.

Tversky, B. and Lee, P. (1998) : How space structures language. In C. Freksa, C. Habel, K. Wender, (eds) : *Spatial Cognition*, pp.157-175. Berlin: Springer-Verlag.

Witmer, B.G, bailey, J.H., Knerr, B.W. and Parsons, K.C. (1996): Virtual Spaces and real world places: transfer of route knowledge. *International Journal of Human-Computer Studies*, vol. 45, pp. 413-428.

Yates, F. (1969): *The Art of Memory*. New York: Penguin.