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ORIGINAL ARTICLE

Remote collaboration in virtual reality: asymmetrical effects of task distribution on spatial processing and mental workload

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Abstract In the context of a remote collaboration task in virtual reality, this study aimed to analyze the effects of task distribution on the processing of spatial information and mental workload in spatial dialogs. Pairs of distant participants with specific roles (a guide and a manipulator) had to collaboratively move a virtual object in a plane factory mock-up. The displays allowed the participants to be immersed together in the virtual environment. We analyzed the dialogs that took place according to the frames of reference and the mental transformations required to produce the spatial statements. We also measured the associated mental workload. Results showed that when participants took a perspective, the manipulator's point of view was preferred. Perspective-taking only yielded a moderate increase in mental rotations, which may explain a specifically high mental demand score for the guides' NASA-TLX. Overall, this is in accordance with the least collaborative effort principle. This study reinforces the idea that, in collaboration, operators do not need the same aids as each other. Thus, it is not necessary to develop symmetrical tools, i.e., the same tools for all co-workers; instead, the needs of each operator should be taken into account, according to the task he has to perform. In our case, the guides would be helped with perspective-taking aids, while the manipulators would be helped with action-oriented tools.

Keywords Remote collaboration · Spatial common frame of reference · Spatial cognition · Virtual reality · Mental workload

1 Introduction

Geographically distributed companies use immersive collaborative virtual environments (ICVEs) to integrate expertize located in different sites. An ICVE is a 3D virtual environment shared by at least two remote sites, which uses immersive displays connected through a network (Wang and Tsai 2011). For instance, distributed teams may meet remotely in a virtual plane mock-up to plan scheduling changes in the industrial process of plane construction. Engineers, represented by avatars, are immersed in the plane and connected via phones. Later, in the real factory, they can decide collectively the best way to operate. Such new technical devices raise new questions about how people collaborate. While some studies have already looked at remote collaboration (Churchill et al. 2001; Wang and Tsai 2011), few have focused on the spatiality of these virtual environments (Chellali et al. 2012). In this study, we are particularly interested in the construction of the shared representation of the environment and the link to the collective management of the mental workload.

Every operator has a singular mental representation of the situation. Endsley (1995) called this representation "situation awareness". During spatial tasks, such as navigation, the spatial representation of the environment is an important part of situation awareness (Finlay et al. 2007; Foo et al. 2007). In a collaborative activity, to ensure

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mutual understanding and good coordination of tasks, the collaborators need to build a shared mental representation of the situation: the common frame of reference (Hoc 2001; Chellali et al. 2012; Schouten et al. 2013). This is also called the common ground—"that is, mutual knowledge, mutual beliefs, and mutual assumptions" (Clark and Brennan 1991). To build this representation, both collaborators need to attribute some knowledge to their co-worker: They have to take into account the singular mental representation of the other. In spatial tasks, an important question is how operators represent and share space. To exchange spatial information, collaborators use verbal communication. Clark and Brennan (1991) pointed out that communication is a collective activity in which people have to coordinate on content. They argued in favor of a principle of least collaborative effort: "In conversation, the participants try to minimize their collaborative effort—the work that both do from the initiation of each contribution to its mutual acceptance." This principle replaces the least (individual) effort principle. Many studies about spatial dialogs have argued in favor of least collaborative effort (Schober 1995; Pouliquen-Lardy et al. 2015). Roger et al. (2013) showed that during a remote navigation task, roles (i.e., guides or those being guided) influenced spatial communication. Guides introduced more landmarks than those being guided and were also more likely to use perspective-taking. In their study, asymmetry was induced by task distribution (between the guides and the guided) and also by the technical device used: Only the guided person could physically explore the (real) environment. The difference with the context of ICVE is that both collaborators are immersed in the same virtual environment: they can see each other, but both of them have mediated experience of the environment.

Clark and Brennan (1991) listed the different sources of costs in dialog. For the situations we are interested in, we will retain the production and understanding costs. Many studies have pointed out that the time needed to take another perspective varies with the degree of rotation (Roberts and Aman 1993; Schober 1995; Michelon and Zacks 2006; Duran et al. 2011). For example, if Peter and some friends are in the same car, and Peter says, "look right, there is a beautiful rainbow", neither he nor his friends have to operate any mental transformation to understand where the rainbow is located. Conversely, if Peter is facing Maria and says, "can you give me the glass on your right, please?" he has to operate a 180° mental rotation to take Maria's perspective. At the same time, Maria does not have to perform a mental transformation to understand which glass Peter is talking about. Thus, the relative orientation of the speakers is required in order to determine what kind of mental transformation is needed. In addition, it is not always necessary to operate mental rotation, particularly when no perspective is taken. For instance, if Thomas is waiting for Karl at the door of a building, watching the lobby, and says to Karl, "be careful when you come down, because there is a puddle in the lobby", Thomas has no mental transformation to operate because the scene is available for him. Karl, on the other hand, has to mentally imagine the lobby ("imaginal updating", see Hintzman et al. 1981; Riecke et al. 2007). As Roskos-Ewoldsen et al. (1998) argued, even if location is encoded in an orientation-dependent manner, Karl can choose his preferred perspective because Thomas's utterance does not impose any particular point of view (i.e., it is perspective-free). The current study will look at mental transformation requirements for each utterance in order to complete a frames of reference analysis and get a better understanding of the costs of producing and understanding spatial statements. However, although mental transformation requirements can identify any cognitive costs, they cannot measure them. Online measurement of cognitive workload is difficult. However, it would be interesting to see if both guides and manipulators experience the same cognitive effort during the task. Indeed, the least collaborative principle suggests that, in some situations, people may individually assume a higher cost in order to reduce collaborative cost (Clark and Brennan 1991). While spatial dialog informs about the verbal strategies, it does not inform directly about the cognitive workload. Moreover, to our knowledge, no study yet exists which looks at spatial dialog and mental workload measurements at the same time.

The current study is focused on spatial communication during remote collaboration in ICVEs. A manipulator had to move a virtual object according to the instructions given by a guide. Collaborators were immersed in the same virtual environment. They were represented by avatars and interacted over the phone. Dialogs were recorded, transcribed and analyzed. We looked at the frames of references used and the mental transformations required to produce and understand each spatial utterance. Finally, participants evaluated the cognitive workload needed to perform the whole task. According to the least collaborative principle, the aim of the current study was to test three closely related hypotheses.

- First, the choice of the reference frames used may be determined by role asymmetry and the requirements of the task. Since the guide gives information to the manipulator, he will be more likely to take the other's perspective (Roger et al. 2013).
- Second, changing the perspective imposes spatial transformations, including mental rotations, which will have a cognitive cost.
- Third, both speakers will produce spatial statements that serve to minimize their collaborative effort.

2 Method

To study spatial communication in remote collaboration, we proposed a naturalistic collaborative spatial task to be carried out between two participants. The task consisted of moving an object from one point to two others in a constraint-based ICVE. One participant moved the object (manipulator), while the other guided him (guide).

2.1 Participants

Twenty-eight native French speakers participated in this study (6 women, 22 men; mean age 24 years, age range 20–54). Participants comprised either undergraduate students from Ecole Centrale de Nantes (23 participants) or interns working for Airbus Group (five participants). Only one of them had previous experience of virtual reality systems. They worked in pairs (six male–female pairs, eight male pairs). Some studies have shown lower levels of performance in spatial tasks for women (Lawton 2001; Kimura 2001; Kolb and Whishaw 2002). Thus, no female pairs were formed in our study and the role attribution was balanced, with three women assigned the guide role, and three the manipulator role.

2.2 Apparatus

For each session, two participants collaborated in an ICVE representing an aircraft construction site. We used two immersive walls (3.5 × 2.2 m and 2 × 3 m) with rear double projections for stereoscopy. A tracking system was used both on the glasses (for parallax) and on the joystick (for 3D location and orientation of the pointing laser). The joystick was used for the participants' displacements (in all directions) in the virtual environment and to select menus for object manipulation. Each participant was represented by an avatar composed of a head and a laser (Fig. 1).

2.3 Procedure

Each participant was given a role. He or she was to act as either the guide or the manipulator. The role was described by written explanations followed by a specific training phase. For the guide, the training phase took place in the same virtual environment used for the collaborative session. It represented a generic factory building where a plane was in the process of being assembled and equipped (see Fig. 2a). During his training, he was instructed to visit the three floors of the factory and remember the entrances and obstacles. To ensure he had effectively explored the entire space, he had to draw a map of each floor after training.

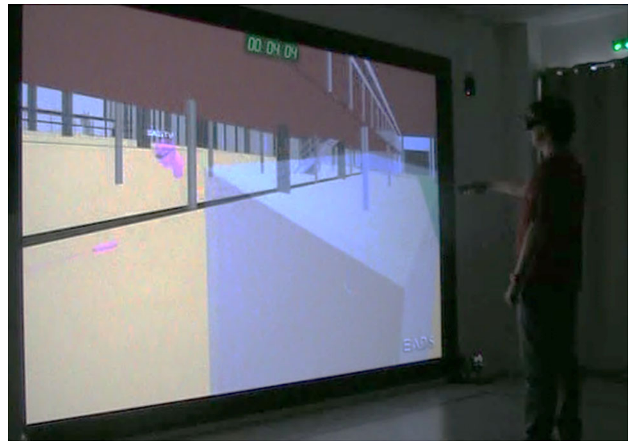

Fig. 1 Picture of a participant in front of the immersive wall. The *pink head* with the *black glasses* on the *left of the picture* is the avatar of the remote collaborator. The *transparent blue cuboid* on the *right* of the screen is the object the manipulator participant had to move in the virtual environment (color figure online)

At the same time, the manipulator received a map with a non-detailed schema of the place (see Fig. 2b). His training took place in an empty virtual building where he had to get used to object manipulation. The target object was a transparent cuboid (.7 × 1 × .7 m, see Fig. 1).

After training, each team had 45 min to move the target object from the starting point (level 0) to two other points (point A in level 1 and point B in level 2, see Fig. 2). To find the only possible solution, collaborators had to deal with four spatial constraints, two for each point. These difficulties were either obstructions (i.e., paths too narrow) or spatial rearrangements (i.e., gate opening).

Once the remote session started, they were free to move in the virtual place and speak through a headset phone. All the sessions were videotaped. The conversations were digitally recorded. After the session ended and a short break, participants answered a questionnaire. It consisted of the National Aeronautics and Space Administration task load index (NASA-TLX; Hart 2006) and a few additional questions. The NASA-TLX is a six-component scale that measures: mental demand, physical demand, temporal demand, performance, and effort and frustration level. Mental demand was measured by asking the following questions: "How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, and searching)? Was the task easy or demanding, simple or complex, exacting or forgiving?" Nygren (1991) has already offered a detailed examination of the NASA-TLX scale. He concluded that the test was efficient enough to solve "workload problems in many applied settings, such as systems development, by accurately predicting operator workload levels both across operators and across a wide range of relevant operator tasks".

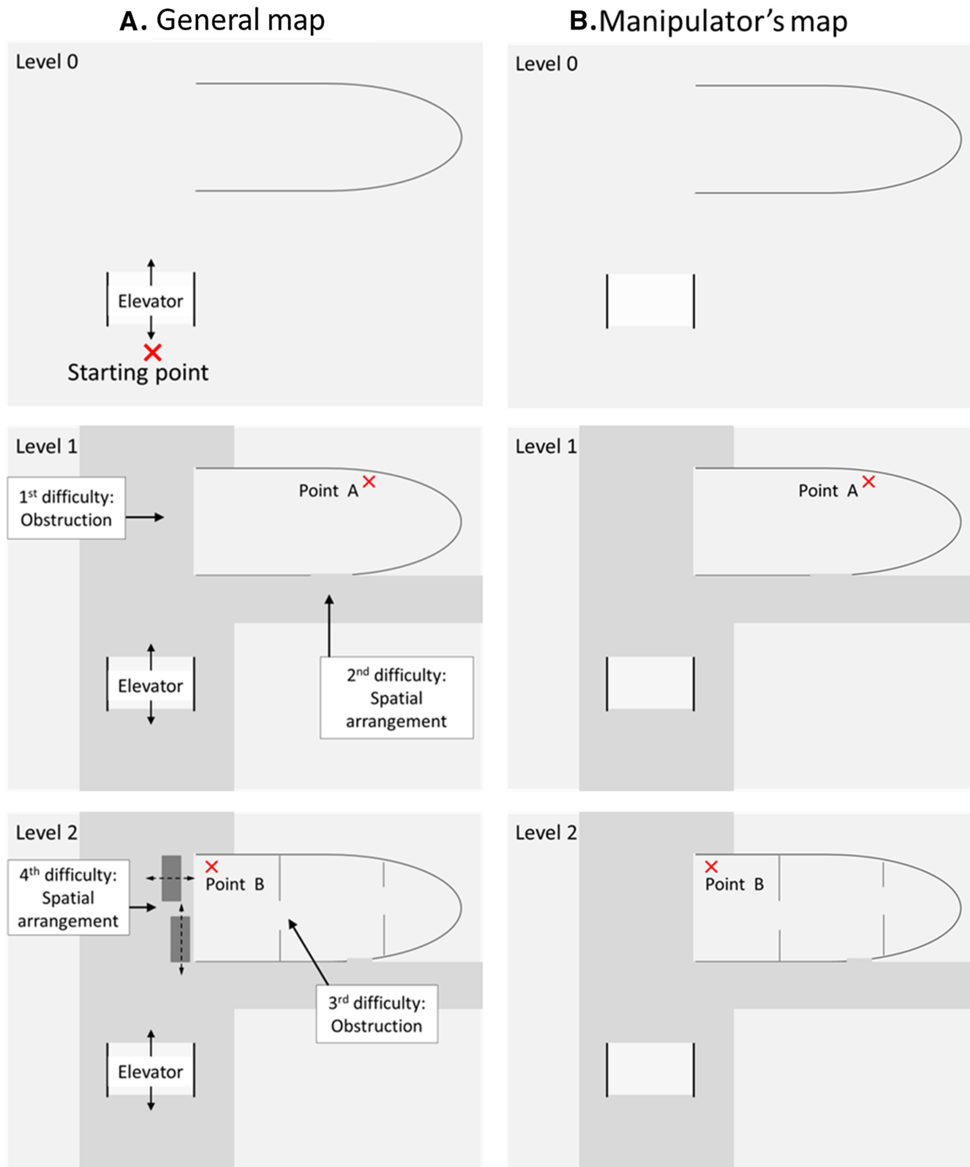

Fig. 2 Map of the collaborative virtual environment. **a** Participants had to move from the starting point (level 0) to point A (level 1) and then to point B (level 2), taking into account four difficulties. **b** Empty map of the environment received by manipulators

Several studies have shown that the properties of a collaborative task can influence the presence in virtual environments (Casanueva and Blake 2000; Chellali et al. 2007). In our study, in order to ascertain whether or not the presence and co-presence feelings influenced collaboration in return, a simplified evaluation procedure was used. The goal was not to measure the presence, for which validated scales already exist (Slater 2009), but rather to check that role attribution did not yield a major difference in that respect. Participants answered two additional questions about the presence feeling ("how did you feel 'there' in the environment?") and co-presence feeling ("Did it feel that your co-worker was present with you in the virtual place?"). This was assessed by means of a 10-cm scale bounded by "absolutely not" and "absolutely".

2.4 Analysis of spatial statements

Videos and conversations were edited with Adobe Premier Elements® and analyzed with Actogram Kronos® (timestamp and coding observations software). In total, 1808 spatial utterances were coded by the first author. The categories were designed to be univocal to ensure an objective coding. Any ambiguous utterances were discarded. This happened on 206 occasions, which resulted in 1602 classified utterances. Each spatial utterance was time stamped and classified in one of the five following categories:

- Neutral: "those that do not depend on any one view" (Schober 1995). This category mainly includes utterances that contain place names (e.g., "let's go to level 1").

- Ego-centered: when the utterance takes the speaker's perspective (e.g., "it is just in front of me").
- Addressee-centered: when the speaker uses the addressee's perspective (e.g., "turn on your right").
- Object-centered: when the reference is an object, usually the plane (e.g., "at the front of the plane").
- Other-centered: when another perspective is needed (e.g., "when you get out of the elevator, it will be just in front of the table").

Each spatial utterance was also classified according to the mental transformation needs. This was achieved through the examination of the videos. For each utterance, two assessments were made: (1) Does the utterance need mental transformation to be carried out by the speaker? This was achieved by assessing the relative orientation of the speaker in the environment and the point of view he was taking when speaking. (2) Does the utterance need mental transformation to be understood by the addressee? This was achieved by assessing the relative orientation of the listener in the environment, and the perspective taken by the speaker when speaking. As explained in the introduction, two mental transformations were identified: mental rotations that require either a change of perspective or other mental transformations based on mental imagery, where no particular perspective is taken (perspective-free). For example, if the guide spoke about a table just near him, but the manipulator was far away and was not able to see the table: "this is near the table" is classified as: (1) no mental transformation for the speaker (guide); and (2) perspective-free transformation for the listener (manipulator), because he needs to imagine the table without taking a particular perspective.

2.5 Data analysis

Four pairs of participants were excluded from the spatial utterances analysis because of the poor quality of the audio recording; however, they were included in the mental workload analysis. Frequency analyses (i.e., counting the number of reference frames used and mental transformations made) were performed using Chi-square tests. Means were compared using bilateral *t* tests. For all tests, the level of significance used was $p < .05$.

3 Results

Descriptively, the guides produced more spatial utterances than the manipulators (respectively, M = 93.2, SD = 50.5 and M = 67.0, SD = 25.0). This difference is not significant due to a large individual variability [$t(18) = 1.46$, $p = .16$].

3.1 Reference frames

The comparison between guides and manipulators showed a significant global difference in the reference frames used [$\chi^2(5, 1602) = 116.08$, $p < .001$], see Fig. 3. The guides used significantly more neutral (referring to the general environment) and addressee-centered utterances than the manipulators [respectively, $\chi^2(1, 1602) = 8.09$, $p < .01$ and $\chi^2(1, 1602) = 76.20$, $p < .001$]. Conversely, the manipulators used significantly more ego-centered utterances than the guides [$\chi^2(1, 1602) = 53.59$, $p < .001$].

Figure 4 shows the evolution of the number of ego-centered and addressee-centered utterances between the first and the fourth quarters of the sessions. The number of addressee-centered utterances increased over time for the guides [$\chi^2(1, 151) = 8.9$, $p < .01$]. Conversely, the number of ego-centered utterances increased for the manipulators [$\chi^2(1, 88) = 14.31$, $p < .001$].

3.2 Mental transformations for the speaker

A comparison of the guides and the manipulators showed a significant global difference in the mental transformations required by the speaker to produce the utterances [$\chi^2(2, 1602) = 116.08$, $p < .001$], see Fig. 5. The guides made significantly more utterances that required mental rotations to be made than the manipulators [$\chi^2(1, 1602) = 34.35$, $p < .001$]. They also made more utterances that did not require any mental transformation [$\chi^2(1, 1602) = 19.44$, $p < .001$].

3.3 Mental transformations for the listener

A comparison of the guides and the manipulators showed a significant global difference in mental transformations required by the listener to understand spatial utterances [$\chi^2(2, 1602) = 45.12$, $p < .001$, see Fig. 6]. The manipulators made significantly more utterances requiring mental rotations to be understood than the guides [$\chi^2(1, 1602) = 40.16$, $p < .001$], i.e., the guides produced fewer utterances requiring mental rotation to be understood, and the manipulators had to make fewer mental rotations to understand what the guides said. The guides produced significantly more utterances that did not require any mental transformation to be understood than the manipulators [$\chi^2(1, 1602) = 20.34$, $p < .001$].

3.4 Questionnaires

Figure 7 presents the means scores of the different subscales of the NASA-TLX questionnaire. The analysis of the global score revealed that the workload was higher for the manipulators than for the guides [$t(12) = 2.52$, $p < .05$]. A components analysis did not show any differences for the manipulators: All subscales yielded similar scores. However,

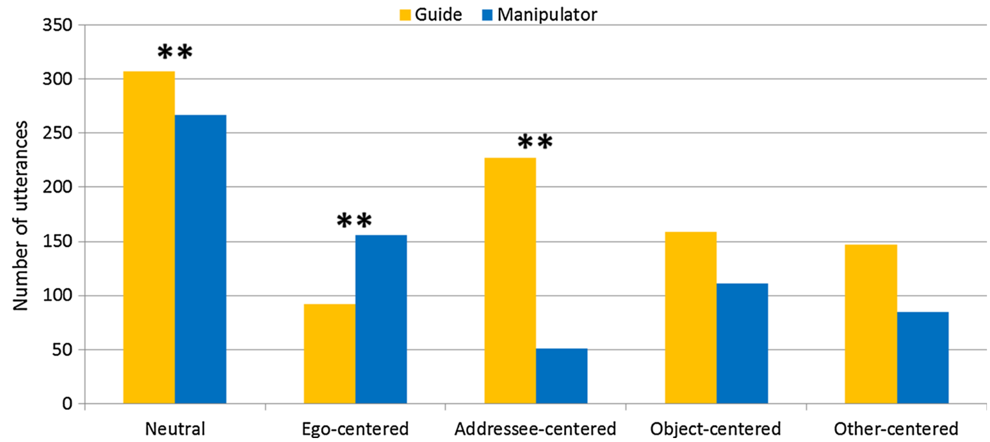

Fig. 3 Total number of spatial utterances produced by the guides and the manipulators. Spatial utterances are classified according to five frames of reference, $^{**}p < .01$

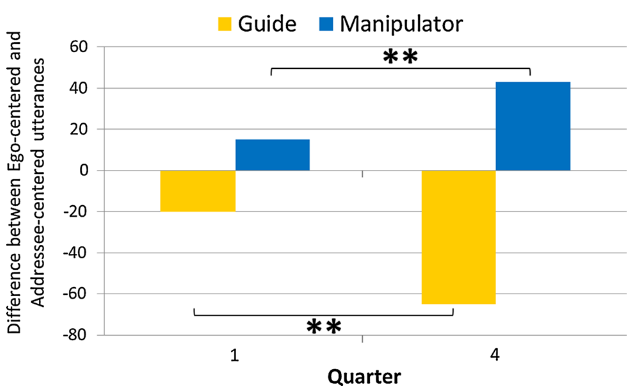

Fig. 4 Difference between ego-centered and addressee-centered utterances produced by the guides and the manipulators for the first (*1*) and the last (*4*) quarters of the sessions, $^{**}p < .01$

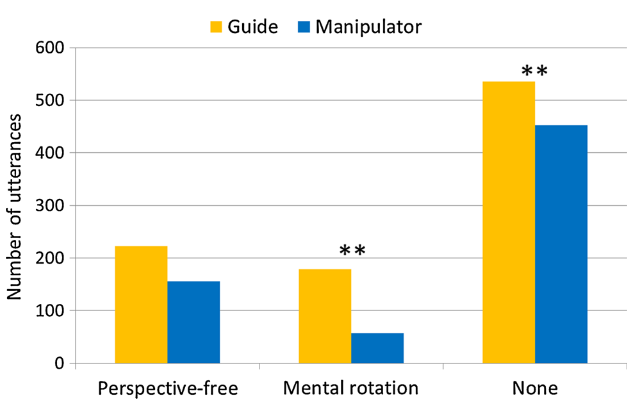

Fig. 5 Number of spatial utterances according to the mental transformations required to be produced, i.e., for the speaker, for the guides and the manipulators. $^{**}p < .01$

for the guides, the mental demand component was significantly higher than all other components ($p < .05$ in all cases).

On the 10-cm scale, on average, people scored their presence feeling at 6.5 cm (SD = 1.9) and co-present feeling at 8 cm (SD = 1.97). There was no difference between the guides and the manipulators [presence: $t(26) = .63$, $p = .53$; co-presence: $t(26) = .54$, $p = .59$].

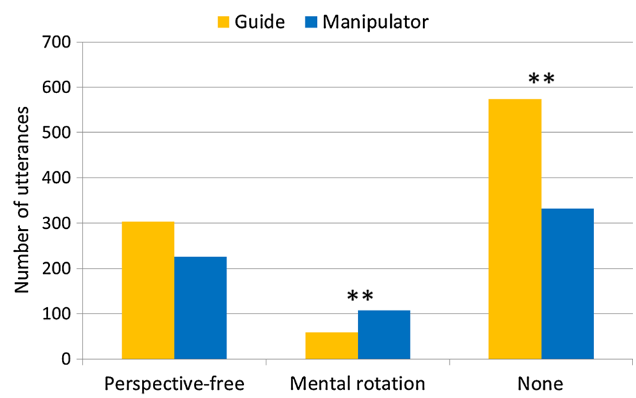

Fig. 6 Number of spatial utterances according to the mental transformations required to be understood, i.e., for the listener, produced by the guides and the manipulators. $^{**}p < .001$

4 Discussion

In the context of remote collaboration using ICVE, the aim of the current study was to investigate how guides and manipulators exchange spatial information. The results show that task distribution influenced spatial information sharing, with the manipulators favoring an ego-centered reference frame, while the guides made more addressee-centered statements. Perspective-taking yielded a moderate increase in mental rotations only, which translated as a specific increase in the mental demand component of mental workload for the guides. Overall, this suggests that the guides tried to diminish the manipulator's workload by taking their point of view, but without imposing too much workload on themselves, in accordance with the least collaborative effort principle.

First, the results show that the guides and the manipulators did not share spatial information in the same way. With regard to perspective-taking, it seems that all the dyads preferentially used the manipulator's perspective. Dialog alignment may reflect a deeper alignment at the level of the representations (Garrod and Pickering 2009). In

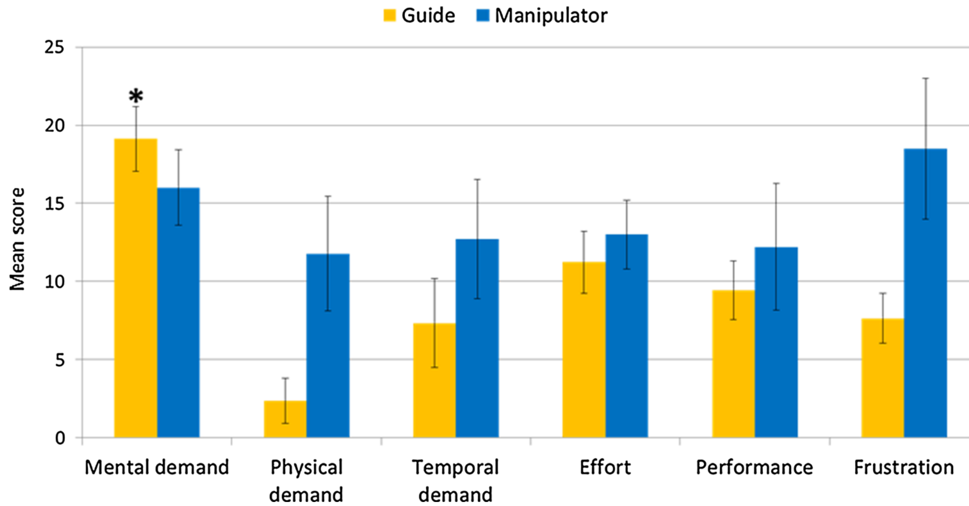

Fig. 7 Mean scores for the six components of the NASA-TLX questionnaire for the guides and the manipulators. The *asterisk* represents the fact that the mental demand score was significantly higher than all other components for the guides only (*$p < .05$)

this study, the common frame of reference was oriented toward the performance of moving the object in the environment. Since the guide provided information to the manipulator, who had to move the object in the environment, both guides and manipulators privileged the manipulator's perspective when sharing spatial information. This strategy was observed early on during the collaboration, but increased markedly over time, as illustrated by Fig. 4. This suggests that the spatial dialog adapted as participants interacted with each other.

Moreover, looking at the frames of reference, the guides produced more exo-centered statements than ego-centered or neutral statements. The high number of perspective changes could have been expected to lead to a massive mental workload. Indeed, it has been repeatedly reported that reaction times increase with the mental rotation necessary to change perspective (Hintzman et al. 1981; Boer 1991; Roberts and Aman 1993; Schober 1995; Michelon and Zacks 2006; Duran et al. 2011). However, the mental transformation analysis revealed that a large part of the statements did not require any mental rotation or perspective-free transformations to be produced. Thus, the guides may have used different strategies to take the perspective of the manipulators and at the same time to minimize their own production costs. They may have moved in the environment in order to be most often aligned with the manipulator's point of view or they may have chosen a perspective (object or other-centered) that was compatible with their current situation in space. This would be consistent with Schober (1995), a study in which neutral statements were preferred when the protagonists were not physically aligned. This strategy minimizes both production and understanding costs. Moreover, the guides minimized the manipulators' understanding costs by producing utterances that did not require any mental transformation. This can be seen as a manifestation of the least collaborative effort: to reduce the cognitive workload of their collaborator, the guides operated perspective-taking, but at the lowest cost to them, too. Of course, this depends on an accurate representation of the whole virtual environment and its spatial configuration. This was only the case for the guides, who had the opportunity to explore the environment before performing the collaborative task. This may be one of the reasons why they chose to take upon themselves the global reduction in mental workload.

Although a large proportion of the spatial statements did not require mental transformations, the guides still had to make more mental rotations than the manipulators in order to make and understand spatial utterances. This did not translate as a global increase in their mental workload, which remained lower than that of the manipulators. However, a specific increase in the mental demand component of the NASA-TLX was observed for the guides only. Mental demand is about "thinking, deciding, calculating, remembering, looking, and searching"; thus, it makes sense that this component alone is affected by the mental rotations that underlie perspective-taking.

The mental workload measurement was performed at the end of the task. Of course, it cannot be attributed only to the spatial dialog. It was also influenced by the difficulty of the task. Overall, the mental workload was higher for the manipulators than for the guides, probably because the manipulation of the object was a demanding task. Further investigations should be carried out to assess if this was an essential condition for the guides to assume more mental rotations. In other words, with equal levels of workload or with more workload associated with the guiding task than to the manipulation task, it remains to be determined how the minimization of the collaborative effort would be achieved.

5 Conclusion

To sum up, task distribution affects spatial communication and associated mental workload. Both the guides and the manipulators centered their common frame of reference on action, i.e., on the manipulator; in so doing, they influenced perspective-taking. This phenomenon required the guides to operate more mental rotations to take the manipulator's point of view and to understand their statements. According to the least collaborative effort principle, since the manipulation task required more mental workload, the guides assumed extra cognitive workload in verbal communication. This suggests that, in order to develop efficient tools in IVCE, it is necessary to take into account asymmetrical task distribution and the associated mental processes. Guides can be helped by the use of perspective-taking aids, such as multiple views, whereas manipulation tools, such as collision visualization, would be more beneficial for manipulators.

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Authors' contributions All authors participated in the design of the study. LPL conducted the experiment. LPL, IM, and FM analyzed the results and wrote the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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