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Bachelor Thesis Cognitive Science

Collaborative Spatial Search – Implementation and Validation of a Multi-User Task in Walkable Virtual Environments

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Abstract

Spatial problem solving tasks are a crucial part of everyday life and encounter us not only in professional, but also in existential situations, such as during emergency response. In most cases, environmental search is performed collaboratively. Despite its importance, it has not yet been thoroughly examined. Understanding the underlying cognitive processes that are involved in solving these problems will help provide supportive software and training methods to make collaborative spatial search more efficient.

The presented study is based on a preceding series of 2D desktop studies conducted by Keilmann et al. [KdlRC+17]. The authors investigated split and search strategies in individual and collaborative search from a bird's eye view on maps, with a focus on the role of a shared mental model during collaboration. The subjects' task was to cover labyrinthine environments *completely* and as *fast* as possible. Keilmann et al. found differences in performance of individual and collaborative searchers depending on the presence of a common frame of reference. The authors confirmed existing evidence of a shared mental model being prerequisite for collaborative advantage [RT+95, CCBS93]; without a common frame of reference, individuals outperformed collaborators.

Since knowledge gained from looking at maps is found to differ considerably from that gained from navigation through environments on foot [MWHR04, MFW+15, MFB13, RMH99], the current work aims at transferring the top-down view desktop study to a walkable large tracking space in which subjects can freely explore virtual environments by physically walking around. This novel setup provides a basis for future research on collaborative environmental search close to reality. Tasks for augmenting the experimental setup included the implementation of networking between the subjects' backpack computers to guarantee a coherent experimental flow in collaborative mode, the restructuring of the software program to provide an easily controllable course of virtual environments in response to the actual movements of the HMD-tracked users, as well as the adaptation of the environments inherited from Keilmann et al. to fit the dimensions of the tracking hall used.

To validate the functionality of the newly built setup, a test study was conducted analogous to Keilmann et al.'s experiment. In contrast to searching maps from a top-down perspective, subjects now had to cover virtual environments by natural locomotion, while a common frame of reference was not provided. Consistent with Keilmann et al.'s outcomes, findings showed that individuals searched more efficiently than collaborative groups. In-depth analysis of search and split strategies applied are suggested. Future investigations should provide a common frame of reference to reveal the predicted differences of search on maps and search through 3D-environments and focus on the nature of cues that support collaborative advantage.

Acknowledgments

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List of Abbreviations

VR	Virtual Reality
HMD	Head Mounted Display

Chapter 1

Introduction

Environmental search is a task we encounter in everyday life. Not only when we are searching for our lost keys at home, or trying to locate our car on a large parking lot, but also in professional life we almost daily have to deal with this issue. In existential situations, such as during emergency response, this has to be achieved above all under extreme physical circumstances and with substantial pressure of time. Despite being heavily equipped, firefighters have only a very limited amount of time to cover an unknown building to find possible victims, before penetrating smoke or flames terminate the operation. The police have to face even larger environments when navigating through an entire city in order to detect a criminal. In most of these situations, search has to be organized collaboratively. However, partners not necessarily share the same background information about the situational circumstances or might not even be present at the same location, as for example the operations managers of a rescue unit and their team. It is also quite conceivable that in the future, not only humans are agents but also robots or drones, which lifts interaction and communication onto a more abstract level. Clearly, there is a diverse range of obstacles that can make successful collaborative environmental search a force-consuming procedure. Therefore, supportive technologies and software for adequate training methods that make suchlike problem solving faster and more efficient, are needed. One might argue that the well-know "Traveling Salesman Problem" in combinatorial optimization theory can provide solutions that humans can profit from for their search. In the traveling salesman problem, the shortest path is to be found that covers all given locations in a closed loop. Despite its tremendous complexity which makes the problem incalculable in adequate time, it does not take mentioned obstacles into consideration. Furthermore, even approximate algorithms can not provide a valid solution for emergency response, since number and location of places that are to be searched in most cases are not known beforehand. Interestingly, human intuitive performance on the traveling salesman problem already shows close to optimal behavior [MO96].

Hence, we need to understand the underlying cognitive processes that are involved in bearing the challenges of human environmental search, so that supportive tools on the basis of assistant information cues can be provided. Emulation of these processes will potentially also help improve computer performance on the theoretical problem [MC11].

Gathering of information about the quality characteristics of the environment investigated is a crucial cognitive task in environmental search which depends on constant updating. For efficient coverage, especially previously already visited locations have to be remembered to minimize the risk of getting lost – the worst-case scenario. At the same time, gain of information trades off against memory requirements since working memory capacity is limited. Thus, memory load should be reduced to a minimum so that unhindered navigation is maintained. Heuristics are known to decrease effort associated with a task [SO08], which is why search strategies constitute an essential component of successful navigation. Different search strategies are found to follow different ways for limiting the utilization of memory capacity. Hölscher et al. [HMV+06], for example, observed a central point strategy in which searchers produce a star-like pattern when always returning to the same point of origin. Therefore, only the way back to this central point has to be remembered.

In collaborative environmental search, agreement between agents on such a strategy is part of planning and of *division of labor*. Such task coordination comprises *communication*, and in most cases, due to spatial distance of agents, this can only be executed verbally. Naturally, communication is also modulated by social processes, such as group identification which is found to be a prerequisite for strong decision performance [SLJ14]. The language used in spatial problem solving also influences performance. Perspective switches during speech, such as from “to my left side” to “to the left side of this wall” exact cognitive costs and hence need to be chosen carefully [TLM99, Sch93].

The main challenges in cooperation arise in establishing a *shared mental model* [HCB+15, RT+95]. First, the problem has to be identified and represented by all agents consistently within a framework which the group members can communicate on [DK00]. This can be facilitated by external environmental properties, such as landmarks which build common orientation cues that can be referred to. Furthermore, expertise of individual members of the group has to be shared within this so called transactive memory [Aus03]. Finally, progress has to be monitored constantly and the own as well as the shared mental models are to be updated. Step by step, the current state has to be transformed into the desired target state through individual actions. Particular stages within the whole process might need to be repeated to optimize strategies and to include newly gained information.

There is, as yet, little perceptual research on collaborative spatial search and its underlying cognitive processes. Focus has been put on individual visual search, where subjects have to detect a target item within a visual field filled with distractor items [Wol94]. Findings from visual search, though, can not without any difficulty be transferred to spatial search, since task features differ quite considerably. In spatial search, relevant information might not immediately be accessible and the goal might not pop up visually like in visual search. Also, the search space might not be clear in large environments and therefore, searchers have to move around to acquire information. These spatial transformations go along with different mental representations than those built in visual search rooms [MSB16]. Processes operating on these mental representations also vary, depending on the nature of the search space. Wang and Brockmole found that automatic spatial updating does not occur in all kinds of environments [WB03].

In collaborative cases of visual search, communication works intuitively since the whole search space is visible at first sight and can easily be communicated on and divided up amongst the collaborating team. Verbal communication can even strain performance and therefore nonverbal communication can be favored, as shown in an example of Brennan et al. [BCD+08]. In their eye-tracking study, the authors revealed that the visibility of the partner's gaze suffices for efficient division of labor, and that verbal communication in this case even costs performance quality. As mentioned above, however, nonverbal communication is no option in most cases of spatial search due to potential sight barriers between agents.

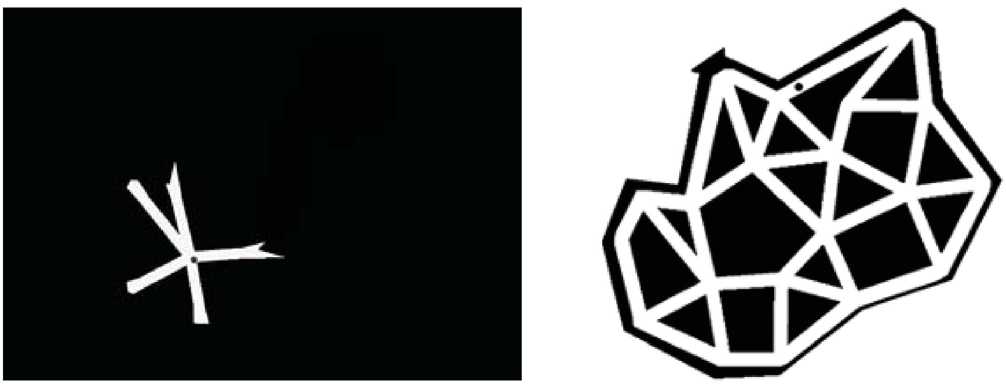
In addition, collaborative problem solving shapes a central field of interest in modern research. In particular, it has been found that collaborative groups perform better than individuals in a wide range of tasks, but not in all tasks [KT04]. For example, a quantitative superiority of groups over individuals' performances has been shown in regard to the number of optimal solutions that were found in making a decision [KT04, Hil82]. Moreover, Hill revealed a collaborative advantage for complex tasks. Still, according to Laughlin [LHSB06], groups are not necessarily better than the best individual.

However, only a few studies have integrated the above fields into one and explored collaborative spatial search as such. I will now introduce work by Keilmann et al. [KdlRC+17] who indeed investigated this question and with their series of studies served as a motivation for the research project presented in this thesis.

1.1 Background: Map Search Studies

Keilmann et al. [KdlRC+17] examined the question of how individuals differ from collaborative dyads in map search, and what role the existence of a shared mental model plays on performance. Two experiments were conducted on a desktop computer where participants either individually or collaboratively searched environments from a top-down map perspective. Labyrinthine environments were randomly generated and differed in number of intersections to vary complexity. The task given was to search the whole environment, i.e. collect all invisible pickup items at each intersection and corridor, as fast as possible. Movement was controlled using a standard gamepad. Each participant searched all environments twice – once individually and once collaboratively with a partner. In the first experiment, participants only saw corridors within the field of view from their current position (see figure 1.1 a). In the second study, the entire map was permanently visible during the whole experiment (see figure 1.1 b). This was done to provide both subjects with a common frame of reference, which enabled search being based on a shared mental model. Verbal communication with the partner was allowed in both experiments, but partner subjects did not see each other. In the collaborative condition, the partner's position was only visible on the map, if it was located within the own area of visibility.

The authors found that collaborative groups' performance can be both better and worse than individuals'. Performance was measured by two main parameters, as well as a combination of both as a measure for efficiency. First, the *number of missed locations* was examined, which corresponded to the amount of pickup items that were not collected during search. Second, *trajectory length* was computed from the recorded positions of subjects during the experiment.



(a) Experiment 1: Only own visual field visible (no shared mental model given)

(b) Experiment 2: Whole map visible (shared mental model given)

Figure 1.1: Stimuli presented in the two preliminary experiments by Keilmann et al. (taken from [KdlRC+17]). Experiments differed in visibility of the map, which was a means for providing participants with a shared mental model (b) or not (a).

Efficiency was defined by trajectory length that was covered before reaching one pickup item.

Comparing individual to collaborative performance in the first experiment, Keilmann et al. found that individual searchers had shorter trajectory lengths and were more efficient than collaborative searchers but missed more pickup items. Also, divergence of performance was greater for more complex environments. In the second experiment, however, collaborative pairs outperformed individuals. This leads to the conclusion that a shared mental model is a prerequisite for collaborative advantage.

Division of labor was measured by the amount of self overlap that subjects produced with their own trajectories. Less self overlap indicated a more successful division of labor. With a shared mental model provided, collaborative pairs not only produced less self overlap than individuals, but this effect was even found to be superadditive. That is, summed up performances of both collaborative searchers were on average even more successful in division of labor than the single performance of one individual.

In short, the presented study by Keilmann et al. confirmed existing evidence of the importance of a shared mental model for collaborative advantage [CCBS93, MHG+00].

In a series of follow-up studies, it will be explored in this work whether previous findings can be replicated in a within-environment setting by means of Virtual Reality (VR), as opposed to the 2D-top-down view on maps used in Keilmann et al.'s study. Additionally, subjects will be provided with the freedom of natural locomotion in a large tracking space, instead of moving a dot via joystick control while themselves remaining stationary. Both of these aspects require considerable restructuring of the experiment's functionality. Therefore, as a start, the current work aimed at implementing all necessary hardware and software-related changes, and at ensuring their coherent functionality by the conduction of a test study. The test study focuses on the comparison of individual with collaborative search without a shared mental model, which corresponds to the experimental design in Keilmann et al.'s first study. In this work, a detailed description of the new setup's implementation will be presented in chapter 2 and subsequently its validity will be demonstrated by the experimental findings of the test study. Implications and an outlook on further investigations will be discussed in chapter 3. To begin with, a brief motivation for switching from map perspective to within-environment-view combined with natural locomotion will be introduced.

1.2 Top-down vs. Within-environment-view

The central difference between the previous and the current experimental setup is the shift from a top-down perspective on environments represented on 2D-maps to being fully immersed within the walkable 3D-environment itself. In the following study, it will be outlined why this step was taken to a within-environment perspective, which involves enormous efforts on both the practical and the theoretical side.

There is considerable evidence, that knowledge gained from map search substantially differs from knowledge gained from navigation through real environments [MWHR04, MFW+15, MFB13, RMH99]. Thorndyke and Hayes-Roth [THR82], for instance, revealed that the survey knowledge acquired from maps supports better judgments of global spatial relations, such as relative distance between objects. Navigation, to the contrary, was found to promote the acquisition of procedural route knowledge which stands out with respect to orienting abilities towards hidden objects.

Maps entail several advantages that alleviate cognitive processing, which cannot be found in real-environment navigation. The constant orientation and reference frame of maps makes identification of a searched location quick, and in contrast to the within-environment perspective, where depth cues might distort perception, maps display a clear layout. The absence of a distinct frame of reference during navigation within real environments puts additional strain on performance in the collaborative case, when searchers have to communicate their locations and division of labor.

On the other hand, physical walking is found to positively influence task performance in regard to several aspects, such as spatial updating [KLB+98], speed [RVB13] and pointing errors [WLH04, WKH01]. A reasonable explanation for this is that path integration is an essential part of navigation. Having access to body-based sensory information, i.e. proprioception, was found to improve the accuracy of cognitive maps [RVB11] and to provide the best subjective sense of presence within the environment, compared to locomotion through alternative modalities, like walking or flying virtually over the environment [UAW+99]. Indeed, it can be argued that these translational and rotational transformations add difficulty to the cognitive problem-solving, but then again, this kind of task is trained extensively in everyday navigation which may consequently compensate for potential costs.

To sum up, performance in spatial search tasks on maps and within walkable environments can vary quite significantly and provoke deviating results. Conclusions drawn from findings on map search must therefore not be transferred to behavior in within-environment navigation. Instead, both settings demand independent investigation.

1.3 Advantages of VR-usage for Research on Spatial Search

For the investigation of spatial search with natural locomotion provided, two alternatives of implementation arise: Studies can either be conducted in real (or specifically constructed) environments, or in virtual environments. The usage of VR-environments has become a popular research tool in general for psychological experiments over the last decades[LBB99]. Until recently, researchers had to trade off ecological validity against experimental control, and since experimental control is considered as the sine qua non of reputable psychological research, in the majority of cases the latter was favored. Since finally VR-technology has matured, become affordable and of satisfactory quality, experimental control can be maintained while keeping ecological validity high. This entails increased generalizability of experimental findings and the theories based on them, close to reality. This is valid especially for studies on spatial navigation, since any number of different environments can easily be created and still be controlled for, and by means of redirected walking even without any limitations in size of space [RKW01]. This technique allows changing the walker's direction without him or her noticing it. Ruddle et al. [RPJ99] directly compared navigation through large scale environments while looking at a desktop screen, with viewing the environments through a head-mounted display (HMD) and found significant differences in performance. Not only did HMD users develop a more accurate sense of distance, but their navigation was also quicker. They benefited from their ability to look around and spent less time stationary to choose the direction to travel.

Furthermore, the crucial application of knowledge gained from research on collaborative spatial search lies in training methods for occupational groups that rely on such cooperation skills. Waller, Hunt and Knapp stressed the effectiveness of training in VR for spatial searchers by stating that "if one is willing to spend enough time, then training in an immersive VE[1] on tasks enquiring route knowledge may surpass map training and be indistinguishable from training in the real world" ([WHK98], p. 141). For disaster-preparedness, this means an immense reduction of costs and risks that real-world training – if possible at all – brings about. Flexibility and stability are also counted among the benefits of virtual training methods of emergency situations, as they provide a repeatable platform unlike any alternative solution [AMP+10]. Examples of such training software have already been implemented [BMMV06, SVLS06] but surely lack further insights into the cognitive processes of collaborative spatial search and the features and cues that support their efficiency. Due to their complexity, virtual environments have to be designed carefully to match

[1] VE here stands for virtual environment.

the intended users-characteristics and provide an optimal solution for their intended application [CS98].

These differences illustrated above emphasize the importance of including natural locomotion in virtual environments into research on collaborative spatial search.

Chapter 2

Experiment

The study presented in this thesis adopted structure and task from Keilmann et al. [KdlRC+17]. Participants were asked to imagine to be fire fighters and cover virtual environments of varying complexity – either alone or as a pair – completely and as fast as possible.

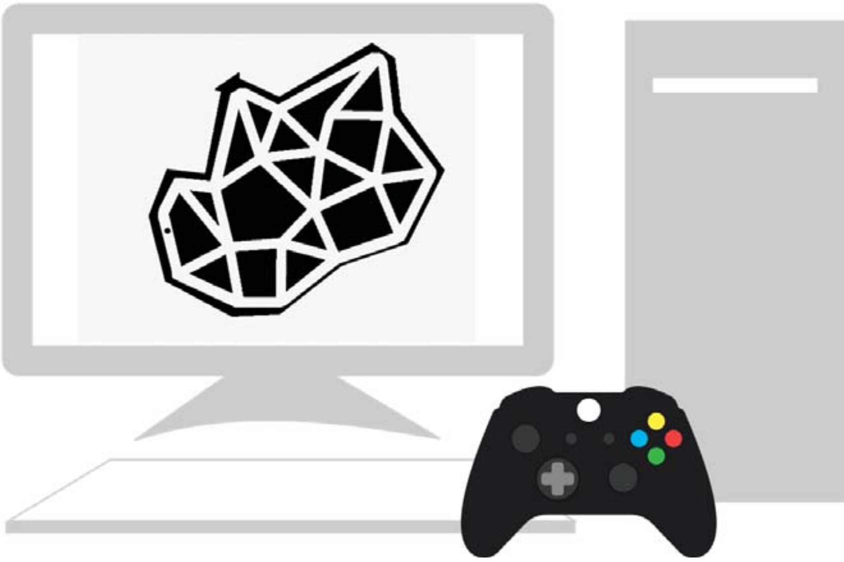
Beyond that, the current work differs from Keilmann et al. in two crucial aspects: the perspective was changed from a top-down view on 2D maps to being immersed in virtual 3D environments, and position now follows natural locomotion, in contrast to being controlled by joystick previously. Therefore, the functionality of several features of the experimental setup had to be changed or implemented from scratch, such as communication between computers as a consequence of extending the program from one computer controlling both subjects to one computer each. A schematic overview of the main differences can be seen in figure 2.1. Further changes will be addressed in the following chapter.

Analysis focused on the comparison of individual with collaborative performance, in terms of distance traveled and number of missed locations. In addition, division of labor was looked at. Even though a differentiated analysis of search strategies was beyond the scope of this thesis work, various strategies will be discussed exemplarily in Chapter 3. A shared mental model was not provided, which makes the experiment analogous to Keilmann et al.'s first experiment.

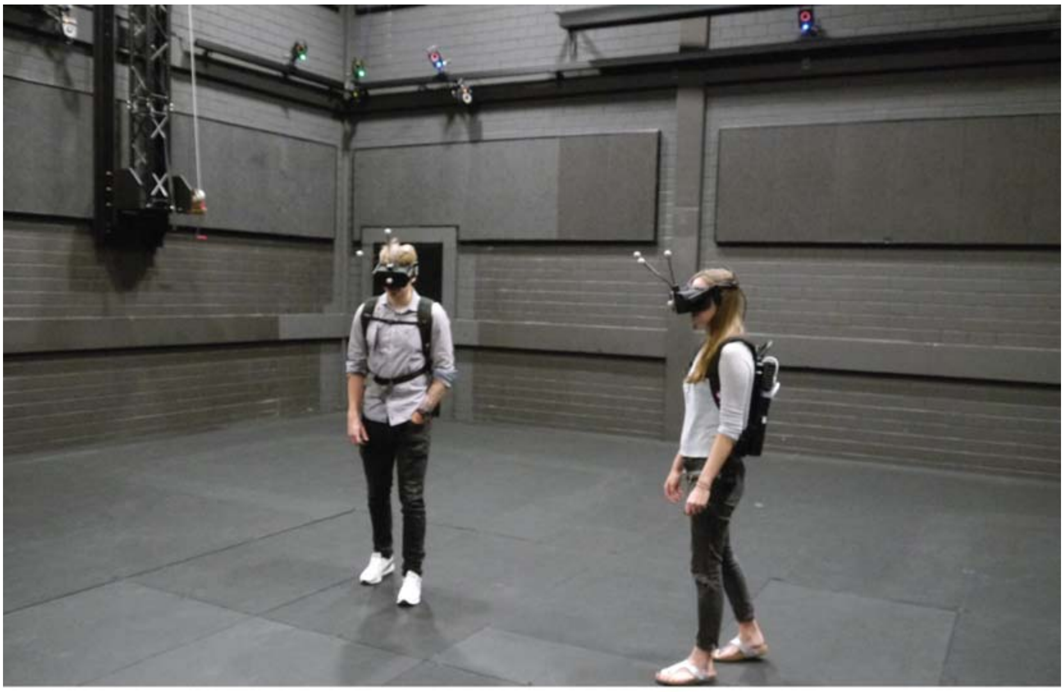
2.1 Method

2.1.1 Participants

Twenty volunteers (seven females), i.e. ten dyads, participated in the experiment and were compensated for their time at the rate of 8 Euro per hour. They



(a) Previous experimental setup



(b) Current experimental setup

Figure 2.1: Illustration of the experimental shift from the previous desktop-PC study by Keilmann et al. [KdlRC+17] (note that two screens and two controllers were used on one computer) (a) to the current studies in the large tracking hall used. Now, two backpack computers communicate via a networking system. In the background, the wall-mounted infrared cameras used for tracking can be seen (b).

(a) Equipment **(b)** Remote control

Figure 2.2: A fully equipped subject wore a trackable HMD connected to a backpack computer (a) and held a one-button remote control in one hand (b).

ranged in age from 20 to 29 years (mean = 25.4, SD = 2.48). All participants gave their written informed consent before beginning the study.

2.1.2 Setup

The experiment was carried out in a 12 m × 15 m large, fully position tracked hall which enabled free walking for users. Each subject wore a MSI VR ONE 7RE-083 backpack computer and an Oculus Rift CV1 HMD connected to it, including on-ear headphones (see figure 2.2 a), and held a remote control in one hand (see figure 2.2 b). The subjects' head positions were tracked using 20 Vicon MX13 optical camera systems based on near infrared reflective markers that were installed on the subjects' HMDs. Each camera sensor had a resolution of 1280 × 1024 pixels and the system was run at a frame rate of 180 Hz. Tracking not only enabled updating of the virtual environment viewed by the participants and the subject's virtual position but also served as a recording tool of the participants' positions for later analysis. Networking between computers allowed shared state representations to provide a coherent flow of experimental phases for both subjects.

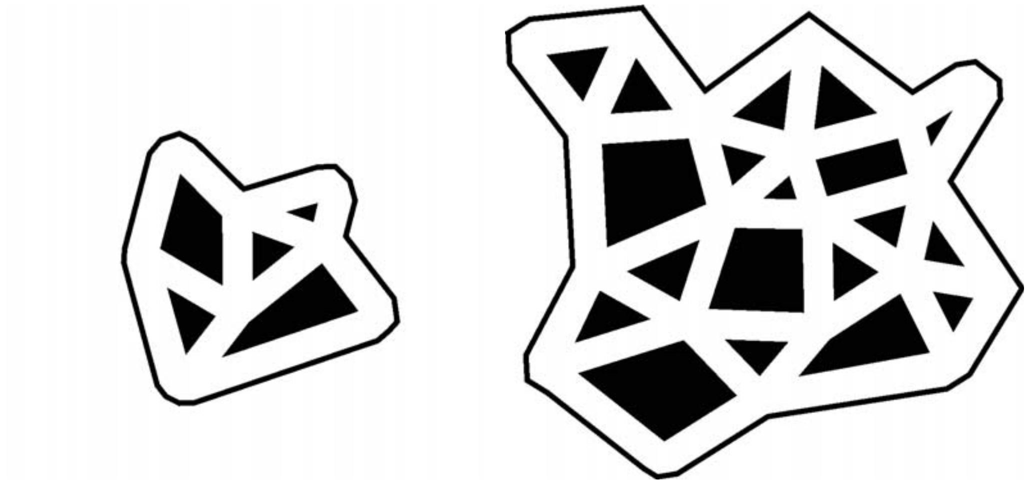
2.1.3 Stimuli

The experiment was programmed with Unity version 5.50f3. The course of the experiment was maintained, analogous to Keilmann et al., but the program structure was fundamentally changed and simplified, in order to provide an easily alterable basis for future experiments. The 3D models of the virtual environments were built with SketchUp 2017 on the basis of existing labyrinthine networks which were inherited from Keilmann et al. These authors constructed an algorithm beforehand, which randomly computed the networks. This algorithm ensured a homogeneous distribution of intersections, at which two to five corridors meet in a way that no straight routes across an intersection occur [KdlRC+17]. Eighteen environments of six complexity levels (5, 8, 11, 14, 17, or 20 intersections) were generated, but only ten environments of five complexity levels (8 - 20 intersections) were used in the current experiment with an average corridor length of 2.44 m (see figure 2.3). The 5-intersection environment was not found to show any effects in the previous study ([KdlRC+17]) and was therefore only used for training in the current experiment. Also, one of the largest environments had to be excluded due to spatial limitations of the tracking hall used and hence total extent of environments was reduced to two per complexity. The original environments used by Keilmann et al. had to be rescaled for this experiment to fit the size of the tracking hall. As a side-effect of rescaling, corridors appeared too narrow to walk through naturally and on account of this, their width had to be broadened retroactively.

Starting positions were set randomly. At the middle of each corridor, as well as at each intersection, there was an invisible pickup item placed, with a total amount of pickups varying between 20 and 58 items, depending on the complexity of the environment. Pickup items played a sound at collection (i.e. physical movement of either participant over the position of the item for the first time, but not afterward). Participants only heard a sound when collecting a pickup item themselves, but not when their partner collected it. In order to prevent subjects from locating each other's position within the environment, background water noise was constantly played over the headphones. In the virtual environment, the partner participant was represented by a 1.8 m high capsule.

2.1.4 Design

For the experiment, a 2 × 5 × 2 within-subject-design was utilized with conditions varying in *cooperation mode* (individual, or collaborative in dyads) and *complexity of the environment* (8, 11, 14, 17, or 20 intersections per environment). One experimental session consisted of ten different environments, since complexity of the environment was repeated twice. Every ten frames during a trial, participants' positions and the number of collected pickup items were



(a) Small Environment **(b)** Large Environment

Figure 2.3: Examples of a small environment with 8 intersections (a) and a large environment with 20 intersections (b).

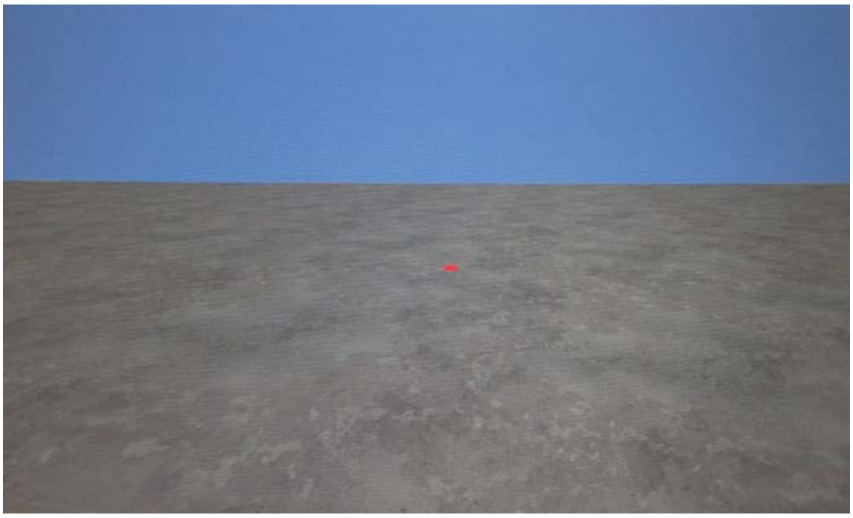
recorded. For later analysis, the number of missed pickup items, trajectory lengths, as well as the time passed since start were computed.

2.1.5 Procedure

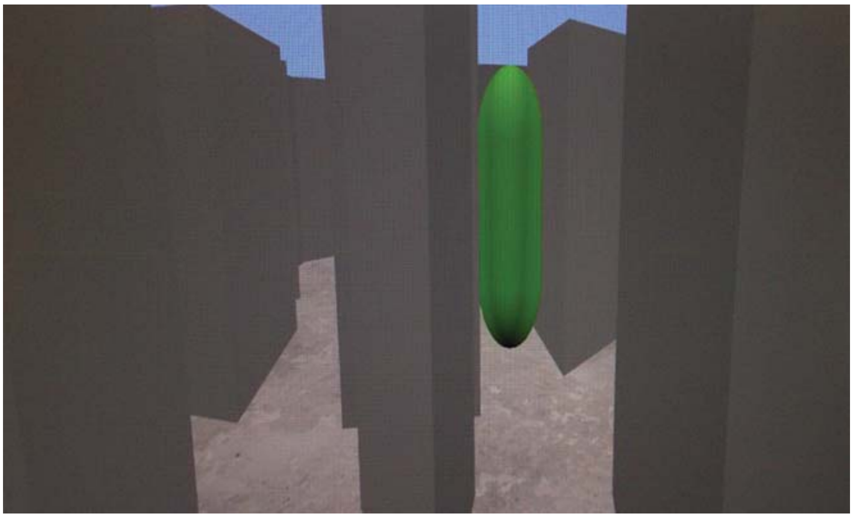
Participants were tested in pairs of two and conducted two experimental sessions: one collaborative in dyads, and one individual, while the other person sat waiting in a separate room. Half of the pairs started with the collaborative part, the other half with the individual part.

Prior to the start of the first session, both participants received written and oral instructions. They were asked to imagine they were firefighters searching a floor for victims and their task was to search **the whole floor** (collaboratively or individually) **as fast as possible**. In order to prevent subjects from bumping into each other in the collaborative condition, they were asked to walk at a normal pace and not run; also, progress was constantly monitored by the experimenter in order to be able to intervene in relevant situations such as impeding collision. Subsequently, participants were helped into the equipment and a training depending on cooperation mode started. This was done to ensure that participants were comfortable with the equipment and walking freely whilst viewing a virtual environment. The training consisted of a 5-, an 8-, and an 11-intersections environment and could be repeated as often as wanted by the participant.

One experimental session consisted of ten trials. Trials differed in complexity of environment to search. There were five complexity levels with two environments each, presented in a randomized order for every session. A trial started with an instruction screen, during which participants were allowed to talk to each other in the collaborative condition. Here, the background water noise was paused. Participants were not allowed to talk to each other during the rest of the experiment, in order to control for audible cues to locate each other's positions. The talking phase was followed by a phase for finding the red-dot starting position on a seemingly endless plane (see figure 2.4 a) and finally the actual task commenced within the environment (see figure 2.4 b).



(a) Finding the starting position

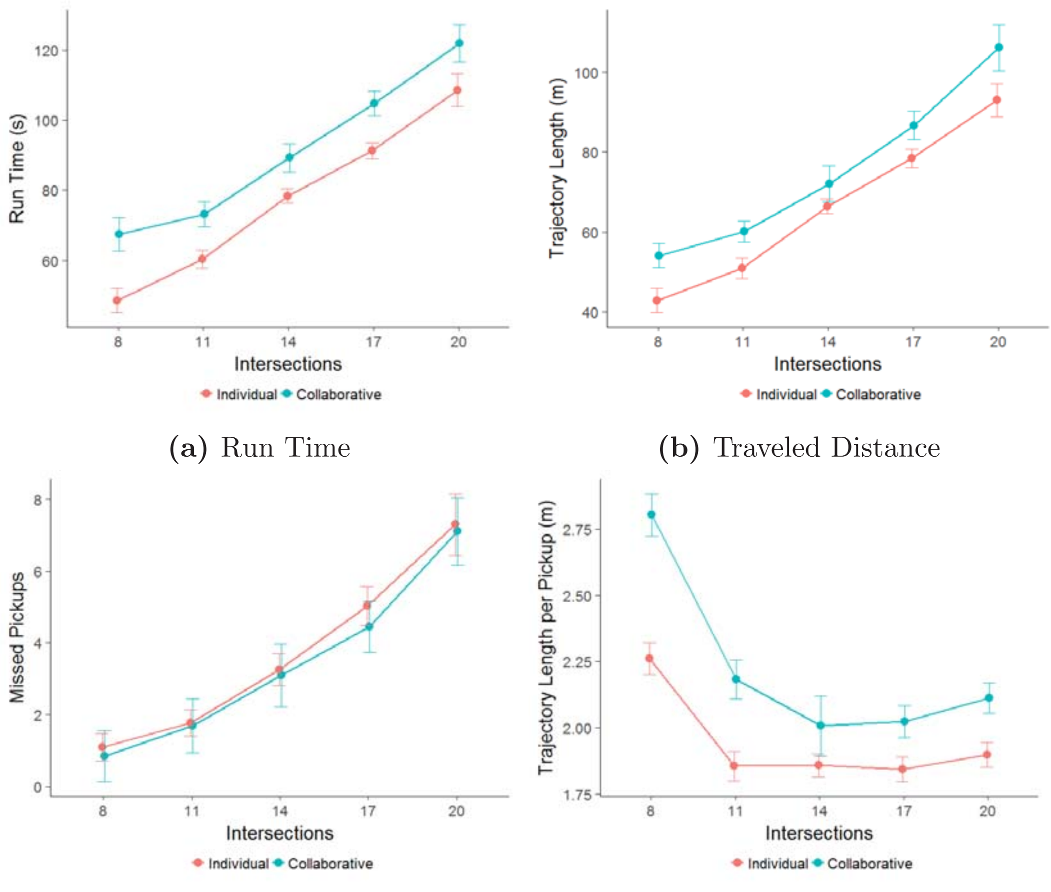


(b) Searching the environment

Figure 2.4: Examples of views when finding the starting position, represented by a red dot on the ground (a), and during task performance within the environment, with the dyad-partner represented by a green capsule (b).

2.2 Results

Performance measurement data was analyzed with an ANOVA on a linear mixed effects model with within-participants factors *cooperation mode* (individual/collaborative) and *complexity of environment* (number of intersections). For comparison of trajectory lengths and run times of both cooperation modes, individual performances of both dyad-members were added up. Thus, their summed up performances were compared with the performances of the individual searchers. Added up over all experimental sessions and all participants, a total of 6.85 man hours has been spent in spatial search covering 20.9 km of trajectory length.



(a) Run Time

(b) Traveled Distance

(c) Missed Locations

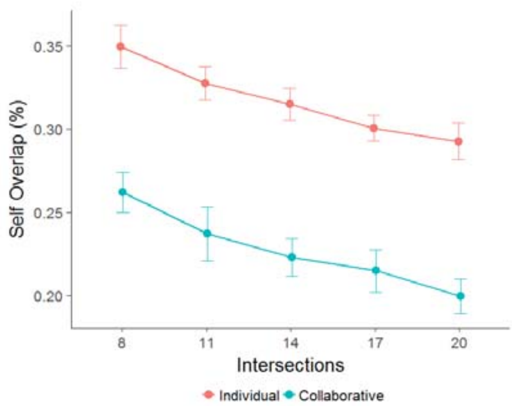
(d) Efficiency

Figure 2.5: Means and standard errors in terms of time taken to finish (a), traveled distance (b) number of missed locations (c), and distance to travel until reaching one pickup item as a measure for efficiency (d) are shown per complexity level (number of intersections) and compared for individual and collaborative performances.

The analysis revealed that complexity of environment had a significant influence on task performance for all measurements. For less complex environments, subjects took less time to finish ($F(4,\ 66.2) = 57.5$, $p < .001$; see figure 2.5 a), traveled shorter distances ($F(4,\ 60.7) = 64.3$, $p < .001$; see figure 2.5 b), and missed less pickup items ($F(4,\ 63.4) = 28.1$, $p < .001$; see figure 2.5 c). Cooperation mode had a significant effect on run time ($F(1,\ 9.53) = 15.2$, $p = 0.003$) and trajectory length ($F(1,\ 9.04) = 6.74$, $p = 0.029$). Here, individual searchers outperformed collaborative searchers in both aspects, irrespective of environmental complexity (see figure 2.5 a and b). Comparable outcomes for analysis of both factors, run time and trajectory length, indicate that subjects walked with constant velocity. Collaborative and individual searchers showed no difference in number of missed pickup items (see figure 2.5 c).

Efficiency was analyzed as a function of trajectory length per pickup, i.e. the average distance a participant had to travel to reach one pickup item. Significance was found for both main effects cooperation mode ($F(1,\ 9.04) = 6.35$, $p = 0.033$) and complexity of environment $F(4,\ 250) = 34.7$, $p < .001$). The effects were modulated by an interaction ($F(4,\ 250) = 3.18$, $p = 0.014$). There was a clear advantage of individual over collaborative search in terms of efficiency, whilst decrease of efficiency for more extreme levels of complexity (very small or very large) was greater for collaborative groups (see figure 2.5).

In order to quantify division of labor, self overlap was calculated as a percentage of number of locations that were passed more than once and total amount of traveled positions. This was measured for every participant in both, the individual and the collaborative condition, and compared between



(a) Division of Labor

Figure 2.6: Means and standard errors in terms of self overlap as a measure for division of labor are shown per complexity level and compared between cooperation modes.

cooperation modes. Both groups showed less self overlap for more complex environments ($F(4,\ 79.2) = 7.72$, $p < .001$). Analysis also revealed a superadditive benefit for collaborative searchers ($F(1,\ 19.0) = 56.0$, $p < .001$; see figure 2.6). Not only did collaborative groups display less self overlap than individuals, but even the sum of both collaborative searchers' self overlap was less than that of one individual searcher. No other main effects or interactions attained significance.

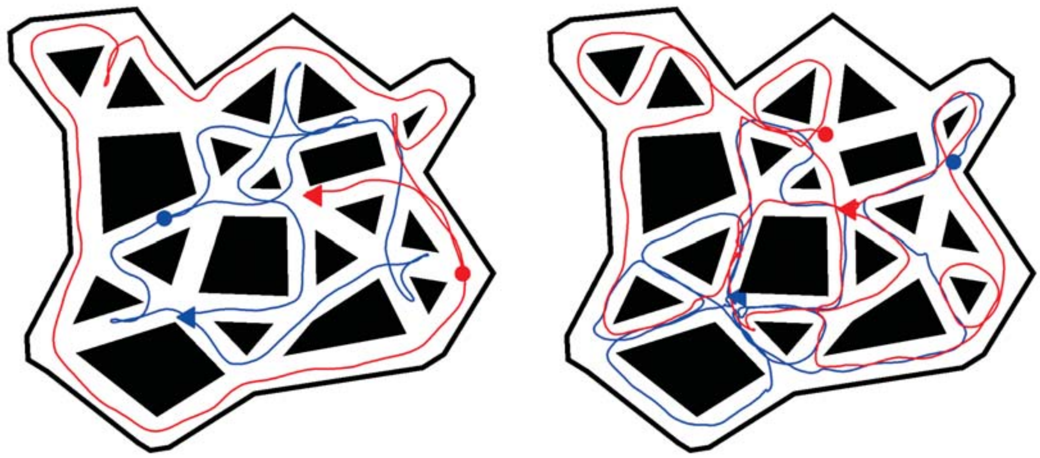
Chapter 3

Discussion

Consistent with Keilmann et al.'s first experiment, it was revealed that without providing a shared mental model, individuals search more efficiently than collaborative groups. The importance of a shared mental model for collaborative advantage over individuals has already been demonstrated in existing literature [RT+95, CCBS93]. In this study, however, despite the absence of a common orientation cue, communication between partners was prohibited during search. Thus, it is conceivable that hindered mutual updating impeded building up a shared mental model about the status quo of the collaborative search. According to Mathieu et al., learning about the states of all team members indeed yields better, more effective performance [MHG+00]. Hence, lack of a common frame of reference might have resulted in collaborative searchers not relying on their partner's performance. Under the assumption that this did not affect both collaborators' motivation to sufficiently fulfill the task, it possibly led each dyad-member to covering the environment overly rigorous, in order to play safe and keep misses low. Presumably, this behavior also serves as an explanation for the shorter distances traveled and overall faster performance of individual searchers, compared to collaborators.

In addition, for both, individuals and collaborative groups, a general tendency towards higher efficiency was found for search in environments of intermediate complexity, relative to search in environments of more extreme levels of complexity (i.e., the lowest and the highest). This raises the question whether there exists a level of complexity of the environment at which groups perform most efficiently. However, slight variation in performance between the environments can also be an outcome of the design of the environments, which should be examined more in detail.

The presence of landmarks is known to significantly improve orientation and therefore overall performance in goal-directed environmental search tasks [RVMB11, SK07]. Nevertheless, in spite of not providing such a common orientation cue in this study, even less self overlap for collaborators was observed, compared to individual searchers. This seems to contradict the longer traveled routes of collaborator, but there are factors that promote such an observation. On the one hand, a reasonable explanation for their smaller amount of self overlap can be that collaborators per person had to cover a smaller area than one searcher alone in the same environment. Smaller areas are likely easier to keep an overview of and as a consequence walking the same routes twice can be avoided more efficiently. On the other hand, a common orientation cue is a crucial prerequisite for teams to divide labor. So, in this case, the only possible effective search strategy to agree on is the perimeter strategy. In this strategy, searchers always stick to the outer wall of the environment and only then explore its inner parts [Tel92, BHW09]. Since subjects did not know where they were initially located within the environment, let alone where their partner was, they could not define regions such as left or right to divide for. The only determinable parameters, which were clearly distinguishable from any position, were the outer wall as opposed to inner parts of the environment. In the exemplary observation of dyad trajectories in the current experiment, indeed a clear preference for the perimeter layout was found (see figure 3.1 a). In cases of no identifiable application of a strategy for division of labor, overlap increased remarkably (see figure 3.1 b), but mostly overlap with the other person's trajectory and not the own. One potential reason for the advantage



(a) Example of a collaboration with relatively efficient division of labor

(b) Example of a collaboration with relatively inefficient division of labor

Figure 3.1: Examples of two performances in the collaborative condition in a complex environment. Both dyads performed equally well in terms of number of missed locations (3), but differed in efficiency of division of labor. Successful division of labor (a), is opposed to unsuccessful division of labor (b). Triangles indicate starting positions, dots specify end positions.

of collaborative groups over individuals concerning self overlap could therefore also be that if a strategy exists, it favors routes that show little self overlap per person. If no clear division of labor was identifiable, though, then apparently dyad-members tended to visit locations that they have not been to before, but accepted that their partner might have covered the same section already. More detailed analysis of the search and split strategies used will provide a more differentiated overview over the benefits and drawbacks of their application and reveal indications about their underlying motivation.

All in all, comparable results to Keilmann et al.'s respective the individual advantage over collaborators in the given conditions were found, which proof the general functionality of the newly created setup. Whether these outcomes indicate that similar underlying cognitive processes control both map and within-environmental search, or if only in the investigated condition of inhibiting the construction of a shared mental model for collaborators results in equivalent behavior in both search spaces, is to be investigated more in depth in follow-up studies. Previous findings suggest that navigation through real or realistic environments in fact evokes deviating results from those gained from search on maps.

3.1 Outlook

Experimental Expansions

The main field of application for findings from research on collaborative environmental search surely lies in the supply of supportive technologies and software for fields of work that access this kind of cooperation every day. These include traffic coordination, such as train and airspace control, as well as emergency response. Consistent with previous findings, the presented outcomes revealed that collaborators in fact are willing to cooperate and profit from their physical and cognitive superiority relative to individuals, but lack opportunity to do so efficiently, as the development of a common frame of reference was hindered. Therefore, as a next step, individual search should be compared to collaborative search while providing a common orientation cue that collaborators can build their shared mental model on. This will help specify the nature of virtual cues that are needed to make collaborative search more efficient. In addition, such an experiment will be analogous to the second experiment conducted by Keilmann et al., in which the authors provided the subjects with a common orientation cue by making the whole map visible for both collaborators. This will complement the experiment presented here and allow a thorough comparison of search from a top-down view on maps with search within walkable virtual environments.

On the basis of the newly formed program, additional features can easily be implemented. A landmark can either be explicitly displayed in the form of a prominent object, such as a steeple in the background, that is visible for all team-members and from any position within the environment. It can also be implemented implicitly by casting shadows on the environment's walls by a virtual sun, that allow drawing conclusions on the relative walking direction. Alternatively, the presentation of a compass needle or a comparable directional cue visible in the field of view of each participant would provide a common sense of direction.

Moreover, to make cooperation easier and permit updating of each others' progress, verbal communication between partners should also be enabled during search. In order to maintain ignorance about each other's position, as it would be the case in most real situations, the presented background noise should be maintained and only muted during verbal communication via headset microphones.

Having said that, information about the partner's position could also explicitly be provided, to investigate if it is worth spending effort on developing software in which the team members' positions are also visible. In the experimental setup realized in this work, this can be implemented by making the virtual environment translucent for the already existing capsular representation of the partner. In real life situations, such as during emergency response, Augmented Reality equipment can be used accordingly, where team members' GPS-positions are being tracked and displayed on the rescuers' visors, for instance.

Technical Improvements

On the technical side of the experiment, a minor side-effect that emerged when conducting the experiment can be improved. Although participants saw their partner represented by a life-sized capsule, when heading simultaneously for the same crossing, time often was too short to react accordingly before nearly to bump into each other. In these cases, the experimenter who permanently monitored the whole procedure intervened, and ordered the subjects to stop. To automatize this process, appropriate mechanisms can be included into the experiment's program. An approach for this purpose is to constantly check the distance between the subjects' head positions and display a warning when they reach a certain range. To ensure that this warning only appears in adequate situations of imminent collision, and not when subjects are walking parallel corridors, for instance, speed of convergence should also be considered. A warning could either be presented acoustically by a "Stop" command, or visually by a hint to reorient.

3.2 Conclusions

In summary, a solid experimental VR-platform was developed enabling close to reality 3D-based research to gain deeper insights into the underlying cognitive processes of collaborative spatial search. In a fully position-tracked space, multiple users can now explore virtual environments by wandering around, and networking between the backpack-worn computers enables their real-time tracking and interaction in complex virtual environments. The execution of a comprehensive multi-user task experiment within this novel setup validated its proper functionality.

In their preceding series of studies, Keilmann et al. [KdlRC+17] investigated individual and collaborative search from a top-down view on maps. In contrast, the presented experiment aimed at the investigation of collaborative and individual search within walkable virtual 3D-environments. Consistent with Keilmann et al., individual searchers outperformed collaborators respective efficiency of search, walked shorter routes, and took less time to finish, than groups. Interestingly collaborative searchers displayed less self overlap, than individuals. The findings were put into the context of existing literature and confirmed results from prior research, as well as, suggested directions for further studies.

Further research, for instance, should extend existing findings that emphasize the importance of a shared mental model for collaborative advantage [RT+95, CCBS93] and investigate its role in the specific case of within-environmental search. The VR-platform developed provides a powerful environment for conducting such advanced studies, and via software extentions can easily be adapted to a broad range of interesting scenarios. Outcomes can help support professional collaborative spatial search, such as during emergency response, by providing technology and software tools, as well as optimizing training methods [BMMV06, SVLS06].

Bibliography

[AMP+10] Pamela B Andreatta, Eric Maslowski, Sean Petty, Woojin Shim, Michael Marsh, Theodore Hall, Susan Stern, and Jen Frankel. Virtual reality triage training provides a viable solution for disaster-preparedness. *Academic emergency medicine*, 17(8):870–876, 2010.

[Aus03] John R Austin. Transactive memory in organizational groups: the effects of content, consensus, specialization, and accuracy on group performance. *Journal of applied psychology*, 88(5):866, 2003.

[BCD+08] Susan E Brennan, Xin Chen, Christopher A Dickinson, Mark B Neider, and Gregory J Zelinsky. Coordinating cognition: The costs and benefits of shared gaze during collaborative search. *Cognition*, 106(3):1465–1477, 2008.

[BHW09] Simon J Buecher, Christoph Holscher, and Jan Wiener. Search strategies and their success in a virtual maze. In *Proceedings of the Cognitive Science Society*, volume 31, 2009.

[BMMV06] Vidhya Balasubramanian, Daniel Massaguer, Sharad Mehrotra, and Nalini Venkatasubramanian. Drillsim: a simulation framework for emergency response drills. In *ISI*, pages 237–248. Springer, 2006.

[CCBS93] Sharolyn Converse, JA Cannon-Bowers, and E Salas. Shared mental models in expert team decision making. *Individual and group decision making: Current*, (1993):221, 1993.

[CS98] Elizabeth F Churchill and Dave Snowdon. Collaborative virtual environments: an introductory review of issues and systems. *Virtual Reality*, 3(1):3–15, 1998.

[DK00] Vanessa Urch Druskat and D Christopher Kayes. Learning versus performance in short-term project teams. *Small group research*, 31(3):328–353, 2000.

[HCB+15] Friedrich Hesse, Esther Care, Juergen Buder, Kai Sassenberg, and Patrick Griffin. A framework for teachable collaborative problem solving skills. In *Assessment and teaching of 21st century skills*, pages 37–56. Springer, 2015.

[Hil82] Gayle W Hill. Group versus individual performance: Are n+ 1 heads better than one? *Psychological bulletin*, 91(3):517, 1982.

[HMV+06] Christoph Hölscher, Tobias Meilinger, Georg Vrachliotis, Martin Brösamle, and Markus Knauff. Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, 26(4):284–299, 2006.

[KdlRC+17] Franziska Keilmann, Stephan de la Rosa, Ulrike Cress, Stephan Schwan, Betty J Mohler, Heinrich H Bülthoff, and Tobias Meilinger. Collaborative cognition beats individual cognition: Advantages of collaborative over individual search require shared task information, and go along but also exceed the better distribution of labor. Manuscript in preparation, 2017.

[KLB+98] Roberta L Klatzky, Jack M Loomis, Andrew C Beall, Sarah S Chance, and Reginald G Golledge. Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological science*, 9(4):293–298, 1998.

[KT04] Norbert L Kerr and R Scott Tindale. Group performance and decision making. *Annu. Rev. Psychol.*, 55:623–655, 2004.

[LBB99] Jack M Loomis, James J Blascovich, and Andrew C Beall. Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers*, 31(4):557–564, 1999.

[LHSB06] Patrick R Laughlin, Erin C Hatch, Jonathan S Silver, and Lee Boh. Groups perform better than the best individuals on letters-to-numbers problems: effects of group size. *Journal of Personality and social Psychology*, 90(4):644, 2006.

[MC11] James N MacGregor and Yun Chu. Human performance on the traveling salesman and related problems: A review. *The Journal of Problem Solving*, 3(2):2, 2011.

[MFB13] Tobias Meilinger, Julia Frankenstein, and Heinrich H Bülthoff. Learning to navigate: experience versus maps. *Cognition*, 129(1):24–30, 2013.

[MFW+15] Tobias Meilinger, Julia Frankenstein, Katsumi Watanabe, Heinrich H Bülthoff, and Christoph Hölscher. Reference frames in learning from maps and navigation. *Psychological research*, 79(6):1000–1008, 2015.

[MHG+00] John E Mathieu, Tonia S Heffner, Gerald F Goodwin, Eduardo Salas, and Janis A Cannon-Bowers. The influence of shared mental models on team process and performance. *Journal of applied psychology*, 85(2):273, 2000.

[MO96] James N MacGregor and Tom Ormerod. Human performance on the traveling salesman problem. *Attention, Perception, & Psychophysics*, 58(4):527–539, 1996.

[MSB16] Tobias Meilinger, Marianne Strickrodt, and Heinrich H Bülthoff. Qualitative differences in memory for vista and environmental spaces are caused by opaque borders, not movement or successive presentation. *Cognition*, 155:77–95, 2016.

[MWHR04] Daniel R Montello, David Waller, Mary Hegarty, and Anthony E Richardson. Spatial memory of real environments, virtual environments, and maps. *Human spatial memory: Remembering where*, pages 251–285, 2004.

[RKW01] Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. Redirected walking. In *Proceedings of EUROGRAPHICS*, volume 9, pages 105–106. Manchester, UK, 2001.

[RMH99] Anthony E Richardson, Daniel R Montello, and Mary Hegarty. Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & cognition*, 27(4):741–750, 1999.

[RPJ99] Roy A Ruddle, Stephen J Payne, and Dylan M Jones. Navigating large-scale virtual environments: what differences occur between helmet-mounted and desk-top displays? *Presence: Teleoperators and Virtual Environments*, 8(2):157–168, 1999.

[RT+95] Jeremy Roschelle, Stephanie D Teasley, et al. The construction of shared knowledge in collaborative problem solving. In *Computer-supported collaborative learning*, volume 128, pages 69–197, 1995.

[RVB11] Roy A Ruddle, Ekaterina Volkova, and Heinrich H Bülthoff. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 18(2):10, 2011.

[RVB13] Roy A Ruddle, Ekaterina Volkova, and Heinrich H Bülthoff. Learning to walk in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 10(2):11, 2013.

[RVMB11] Roy A Ruddle, Ekaterina Volkova, Betty Mohler, and Heinrich H Bülthoff. The effect of landmark and body-based sensory information on route knowledge. *Memory & Cognition*, 39(4):686–699, 2011.

[Sch93] Michael F Schober. Spatial perspective-taking in conversation. *Cognition*, 47(1):1–24, 1993.

[SK07] Brian J Stankiewicz and Amy A Kalia. Acquistion of structural versus object landmark knowledge. *Journal of Experimental Psychology: Human Perception and Performance*, 33(2):378, 2007.

[SLJ14] Kai Sassenberg, Florian Landkammer, and Johann Jacoby. The influence of regulatory focus and group vs. individual goals on the evaluation bias in the context of group decision making. *Journal of Experimental Social Psychology*, 54:153–164, 2014.

[SO08] Anuj K Shah and Daniel M Oppenheimer. Heuristics made easy: an effort-reduction framework. *Psychological bulletin*, 134(2):207, 2008.

[SVLS06] Ameya Shendarkar, Karthik Vasudevan, Seungho Lee, and Young-Jun Son. Crowd simulation for emergency response using bdi agent based on virtual reality. In *Proceedings of the 38th conference on Winter simulation*, pages 545–553. Winter Simulation Conference, 2006.

[Tel92] Jon M Tellevik. Influence of spatial exploration patterns on cognitive mapping by blindfolded sighted persons. *Journal of Visual Impairment & Blindness*, 1992.

[THR82] Perry W Thorndyke and Barbara Hayes-Roth. Differences in spatial knowledge acquired from maps and navigation. *Cognitive psychology*, 14(4):560–589, 1982.

[TLM99] Barbara Tversky, Paul Lee, and Scott Mainwaring. Why do speakers mix perspectives? *Spatial cognition and computation*, 1(4):399–412, 1999.

[UAW+99] Martin Usoh, Kevin Arthur, Mary C Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P Brooks Jr. Walking¿ walking-in-place¿ flying, in virtual environments. In *Proceedings* *of the 26th annual conference on Computer graphics and interactive techniques*, pages 359–364. ACM Press/Addison-Wesley Publishing Co., 1999.

[WB03] Ranxiao Frances Wang and James R Brockmole. Simultaneous spatial updating in nested environments. *Psychonomic bulletin & review*, 10(4):981–986, 2003.

[WHK98] David Waller, Earl Hunt, and David Knapp. The transfer of spatial knowledge in virtual environment training. *Presence: teleoperators and virtual environments*, 7(2):129–143, 1998.

[WKH01] David Waller, David Knapp, and Earl Hunt. Spatial representations of virtual mazes: The role of visual fidelity and individual differences. *Human Factors*, 43(1):147–158, 2001.

[WLH04] David Waller, Jack M Loomis, and Daniel BM Haun. Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin & Review*, 11(1):157–163, 2004.

[Wol94] Jeremy M Wolfe. Guided search 2.0 a revised model of visual search. *Psychonomic bulletin & review*, 1(2):202–238, 1994.

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