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Working Memory in Wayfinding—A Dual Task Experiment in a Virtual City

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Abstract

This study examines the working memory systems involved in human wayfinding. In the learning phase, 24 participants learned two routes in a novel photorealistic virtual environment displayed on a 220° screen while they were disrupted by a visual, a spatial, a verbal, or—in a control group—no secondary task. In the following wayfinding phase, the participants had to find and to "virtually walk" the two routes again. During this wayfinding phase, a number of dependent measures were recorded. This research shows that encoding wayfinding knowledge interfered with the verbal and with the spatial secondary task. These interferences were even stronger than the interference of wayfinding knowledge with the visual secondary task. These findings are consistent with a dual-coding approach of wayfinding knowledge.

Keywords: Working memory; Visual task; Spatial task; Verbal task; Dual task; Virtual reality; Dual coding; Grounding

1. Introduction

> . . . it seems plausible to assume that the [visuo-spatial] sketchpad might have a role [. . .] for spatial orientation and geographical knowledge. So far, there seems to have been little work on this potentially important topic. (Baddeley, 2003, p. 834)

The role of working memory in spatial orientation has rarely been explored. Still, is the intuitive impression true that the visuo-spatial sketchpad is so important? If so, is it the visual or more the spatial component of this subsystem that is linked to wayfinding; and

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how important is the processing of verbal information if humans find their way in known or new environments? In the quotation, Baddeley refers to his working memory theory in which short-term maintenance of information is achieved by the phonological loop (PL), which is responsible for verbal information; the visuo-spatial sketch pad (VSSP); handling visual information, spatial information, or both; and the central executive, which is described as a supervisor responsible for the coordination of the subsystems and the selection of reasoning and storage strategies (Baddeley, 1986, 2003; Baddeley & Hitch, 1974).

So, which subsystem of working memory is essential in human wayfinding? If wayfinders process the wayfinding information in a verbal format (e.g., in the form of verbal directions such as "next left" or "at the church to the right"; cf. Couclelis, 1996; Daniel & Denis, 2004; Denis, 1997; Denis, Pazzaglia, Cornoldi, & Bertolo, 1999; Lovelace, Hegarty, & Montello, 1999), the wayfinding should involve the PL and thus interfere with a verbal secondary task. If the wayfinding knowledge is represented and processed in a visuo-spatial format, it should rely on the VSSP. However, recent studies indicate that the VSSP itself has two subcomponents—one visual and one spatial (e.g., Klauer & Zhao, 2004; McConnell & Quinn, 2000). We therefore applied two visuo-spatial secondary tasks. One secondary task focused on the visual component, the other one focused on the spatial component of the VSSP. If the wayfinding knowledge is represented and processed in a "picture-like" format—for example, in a snapshot of the environment (Mallot & Gillner, 2000) or a map (e.g., Kosslyn, Ball, & Reiser, 1978)—it should rely on the visual component of the VSSP and thus interfere with a visual secondary task. If wayfinding relies on more abstract spatial representations—for example, the geometric layout of an environment (Cheng, 1986; Gallistel, 1990; Wang & Spelke, 2002)—it should involve the spatial component and interfere with a spatial secondary tasks. The goal of this article is to test these competing hypotheses.

2. Method

We used a virtual environment displayed on a 220° screen. The participants learned two different routes through "Virtual Tübingen," a photorealistic model of the medieval city center of Tübingen (see Fig. 1). During this learning phase, participants were disrupted by a visual, a spatial, or a verbal secondary task. In the control condition, no secondary task was given. In the following wayfinding phase, the participants had to find and to "virtually walk" the two routes with a joystick. No secondary task was performed during that phase. In this way, we could measure secondary task interference with the encoding and maintenance of wayfinding knowledge, whereas the wayfinding itself was not disrupted by any secondary task.

2.1. Participants

Twelve female and 12 male participants, mainly students between 19 and 32 years of age ($M = 24$, $SD = 4$) participated in the experiment. None of them had visited Tübingen before. All selected participants were German native speakers and were paid for their participation. Two of original 26 participants did not complete the experiment due to simulator sickness and were, therefore, excluded from all subsequent analysis.

Fig. 1. A snapshot of Virtual Tübingen.

2.2. *Procedure, apparatus, and materials*

The participants sat on a chair positioned 3.5 meters from a circular 220° screen (width: 13 meters; height: 3 meters), which covered the whole horizontal visual field (see Fig. 2). A pc-cluster rendered the projection for an eye position 1.20 meters above the ground referring to average eye height when seated. The frame rate was 60 Hz using 2× hardware anti-aliasing and hardware correction to display the images on the curved screen. Three projectors with a resolution of 1,024 × 768 each projected the pictures. Note that learning and wayfinding phases for each route followed one another immediately (i.e., the learning phase for the first route was immediately followed by the wayfinding phase for the first route, etc.).

2.2.1. *Learning phase*

In the learning phase, the participants were passively carried on two routes through Virtual Tübingen. The transportation speed was 2 meters per second corresponding to a fast walking speed. The 480-meters "long route" consisted of 10 mainly oblique intersections with 23 possible choices (see Fig. 3). Its presentation took 240 sec. With a presentation time of 160 sec and a length of 320 meters, the "short route" consisted of 9 mainly orthogonal intersections with 21 possible choices (for further discussion of these routes, see Meilinger & Knauff, in press). The order of presentation of the routes was counterbalanced among the participants.

Fig. 2. The experimental setup.

While the participants learned a route, they were confronted with one of the secondary tasks: the verbal, the visual, or the spatial secondary task. In the control group, no secondary task had to be completed. We randomly assigned 6 participants to each of the four groups, ensuring an equal number of women and men in each group. All three secondary tasks were

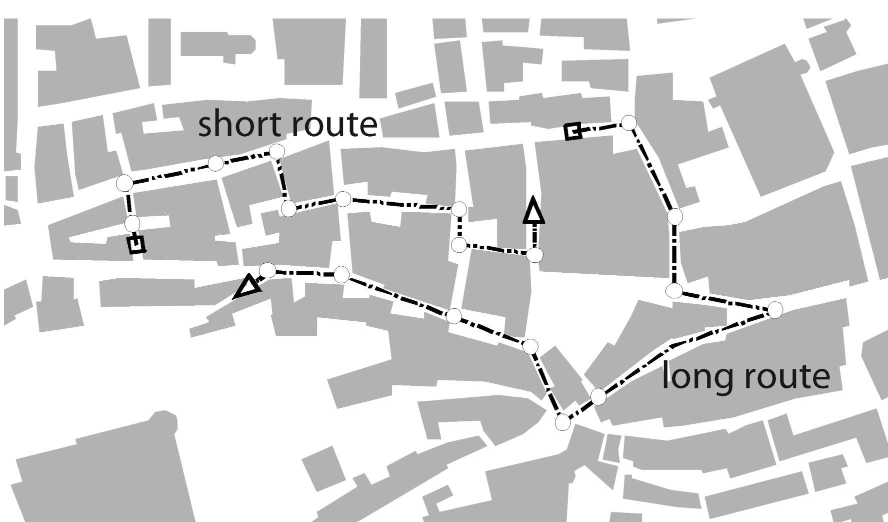

Fig. 3. The two routes through Virtual Tübingen used in the experiment. *Note:* Circles correspond to intersections.

presented via headphones with active noise cancellation. The participants had to respond by pressing a button on a response box. To ensure identical stimuli for all participants and in order to be able to measure secondary task performance, the participants watched a video rather than actively navigated the route.

In the verbal task, the participants had to perform a lexical-decision task. They had to decide whether a presented word existed in German. All 100 German nouns consisted of two syllables and were among the 10,000 most-frequent German words published in newspapers or magazines (Quasthoff, 1998). The 100 non-words not existing in German language were constructed from the 100 words by exchanging the vowel of the first syllable (e.g., "Montag" was changed to "Mintag"). Each vowel was equally often used in the words as well as in the non-words. Therefore, 100 non-words paralleling 100 words were constructed. They were spoken by a television speaker, recorded via microphone, and cut into 200 sound files with the start of the file matching the onset of the vocalization.

In the visual task, the participants heard times and had to imagine a clock with watch hands. For example, at "6 o'clock" the short watch hand points downward, and the long watch hand points upward. Dividing the clock in an upper and a lower half, both watch hands point into different halves. At "12 o'clock" or "20 past 4" both watch hands point into the same half. The participants had to indicate whether the watch hands point to the same or to different halves. All possible times in steps of 5 min were used (e.g., 11:55), with times in the 3rd or 9th hour (e.g., 3:10) and times a quarter to or after an hour (e.g., 5:45) excluded, as at these times the watch hands could not easily be classified as pointing upward or downward. The resulting 100 times of day again were spoken by a television speaker and cut into sound files that started with the onset of the vocalization. The participants were explicitly instructed to solve the tasks by imaging the clock.

In the spatial task, the participants had to indicate from which direction a sound was coming—either from the left, the right, or the front—by pressing one of three corresponding keys. The pleasant sound of a wooden temple block was used for that task. The sound was spatialized using a "Lake DSP Card," with which the sound source can be accurately positioned in space, both in terms of angle and distance to the listener, using a generic head-related transfer function. Again, the sound files started with the onset of the sound.

To ensure that the secondary tasks interfered with the encoding of environmental information, the task difficulties had to be identical. Therefore, the trial durations were adjusted in within-subjects pretests, so that failing to react fast enough was considered an error. The trials followed immediately after each other with no break in between. Very fast reactions in any trial were ignored, as they possibly were initiated during the last trial. Within-subjects pretests with 18 participants led to trial durations of 1.2 sec in the verbal task, 4 sec in the visual task, and 0.8 sec in the spatial task. The corresponding hit rates in the pretests were 86% for the verbal task, 85% for the visual task, and 87% for the spatial task. The task difficulty was assessed the same way as in the baseline condition of the main experiment—that is, while presenting a video showing a walk up and down a street for several times. The area of Virtual Tübingen used for the baseline was not encountered during the rest of the experiment. The participants' task was to keep their eyes open and do the choice reaction task as fast and as accurately as possible. In the main experiment, all participants, including participants from the control group without the secondary task, had to watch this presentation. The baseline lasted 200 sec. This is an average of the 160 sec for presenting the short route and 240 sec for presenting the long route. The order of the items for each secondary task was determined randomly for each participant. We recorded accuracy and reaction time. For the visual and the verbal tasks, the positions of the buttons were selected randomly for each participant. Prior to the baseline, the participants trained with the secondary task for several minutes.

2.2.2. Wayfinding phase

In the wayfinding phase, participants had to walk the two routes by using a joystick to control for heading and forward translation speed. The maximal translation speed was 2 meters per second. In order to reduce simulator sickness, the participants were not able to rotate faster than 30° per second. All relevant parameters were recorded with approximately 100 Hz in order to compute (a) the time from the first movement to reach the goal, (b) the traversed distance, (c) the number of stops, and (d) the number of incidents when participants got lost. Stops were counted if they at least lasted 1 sec and started at least 1 sec after a previous stop. A participant was considered to be lost when turning into a wrong street for about 5 meters. In this case, the participant was stopped by the simulation and had to turn around in order to continue the navigation. From these four parameters we considered "getting lost" the most important. Distance and getting lost correlated by .89 ($n = 24$, $p < .001$). Both measures almost showed identical results, and therefore only getting lost, stops, and time are reported.

Prior to the experiment, the participants were familiarized with the virtual reality setting and the joystick in a small area of Virtual Tübingen not encountered during the rest of the experiment.

3. Results

For the statistical analysis, values deviating more than three standard deviations from the overall mean were replaced by the most extreme value inside this interval. For group differences, one-way analyses of variance (ANOVAs) for performance over both routes were computed followed by planned contrasts between the experimental groups.[1]

3.1. Wayfinding performance

There was a main effect of secondary tasks in the frequency of getting lost (see Fig. 4); ANOVA, $F(3, 20) = 5.43$, $p = .007$; $\eta^2 = 0.45$. The planned single contrasts show that the spatial secondary task influenced the encoding of environmental information used for wayfinding compared to the control group, $t(20) = 3.05$, $p = .006$, $d = 0.62$. Also, the verbal secondary task had an influence, $t(20) = 3.78$, $p = .001$, $d = 0.77$. The visual secondary task had no general significant influence compared to the control group, $t(20) = 1.89$, $p = .074$, $d = 0.39$.

We also compared the groups performing a secondary task with each other (although these tests are not orthogonal). As seen in Fig. 4, the verbal secondary task had a bigger influence than the visual secondary task. This difference attained significance on the short

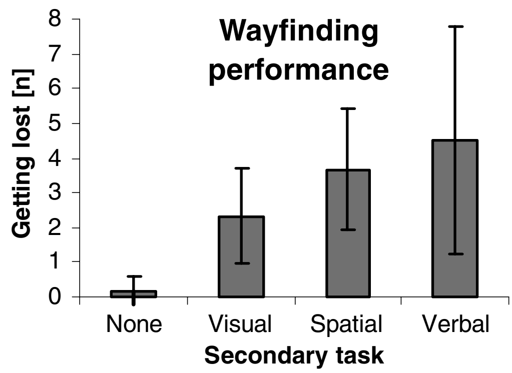

Fig. 4. Getting lost per person on both routes as a function of the secondary task during encoding. *Note:* Means and standard deviations are shown.

route, $t(20) = 2.55$, $p = .019$, $d = 0.52$; but not on the long route, $t(20) = 0.59$, $p = .571$, $d = 0.12$. From visual inspection, the spatial secondary task had a bigger influence than the visual secondary task. This effect nearly attained statistic significance on the short route, $t(20) = 2.03$, $p = .056$, $d = 0.41$; long route, $t(20) = 0.20$, $p = .840$, $d = 0.041$. We found no differences between participants with a spatial and a verbal secondary task, $t(20) = 0.73$, $p = .476$, $d = 0.15$. The histograms in Fig. 5 show that the results were not due to single individuals. There were no effects for time, $F(3, 20) = 2.21$, $p = .118$ ($\eta^2 = .25$), and stops, $F(3, 20) = 0.80$, $p = .510$ ($\eta^2 = .11$), which excludes a speed accuracy trade-off as an explanation for our results.

3.2. Secondary task performance

To rule out the explanation that differences in the main tasks are only due to differences in the secondary tasks, we analyzed the secondary tasks. Overall, the three groups with secondary tasks did not differ in accuracy on the baseline taken before the main experiment (see the left-hand side of Fig. 6): $F(2, 15) = 1.68$, $p = .220$ ($\eta^2 = 0.18$). As in the pretests, the secondary tasks were comparable with regard to their difficulty.

There was also no main effect of secondary task during encoding (see the right-hand side of Fig. 6): $F(2, 15) = 3.12$, $p = .074$ ($\eta^2 = 0.29$). First and secondary tasks did not correlate ($n = 18$, $r = -.24$, $p = .342$). No trade-off between main and secondary tasks, therefore,

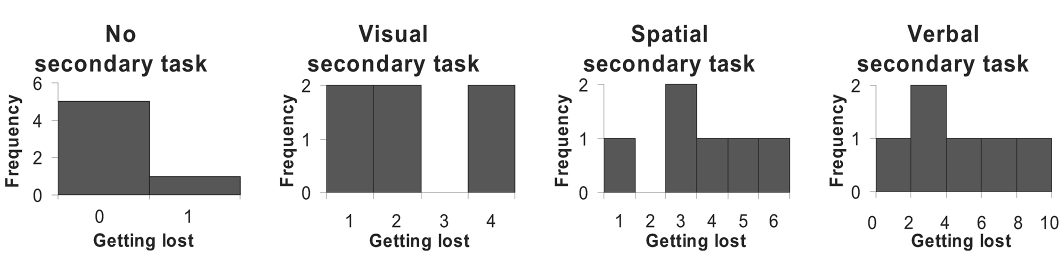

Fig. 5. Histograms for the number of occasions in which each participant got lost during the four conditions.

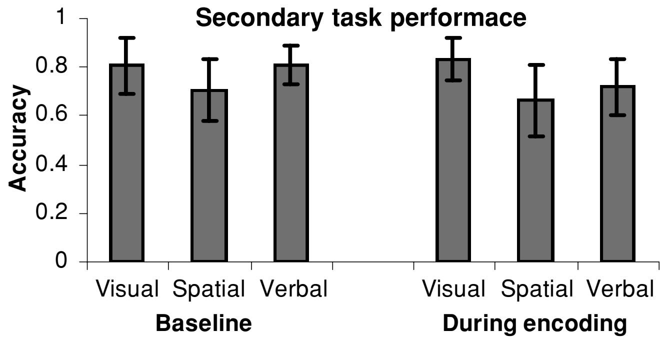

Fig. 6. Accuracy in the secondary tasks during baseline (left) and during encoding of the routes the participants had to “walk” immediately afterward (right).

could explain the results. The direction of the contrasts even point into the same direction as in wayfinding performance: The accuracy in the visual task was higher compared to the spatial task, $t(15) = 2.45$, $p = .027$, $d = 0.58$. The accuracy in the visual task compared to the verbal task showed the same pattern of results, but did not reach significance, $t(15) = 1.66$, $p = .118$, $d = 0.39$. No differences between the spatial and the verbal tasks were found, $t(15) = 0.79$, $p = .444$, $d = 0.19$.

Performance in the secondary task depended on the distance to a decision point (i.e., an intersection). These differences were found for accuracy scores in the verbal secondary task condition (Fig. 7)—overall differences, $F(22, 330) = 2.18$, $p = .002$ ($\eta^2 = .13$)—

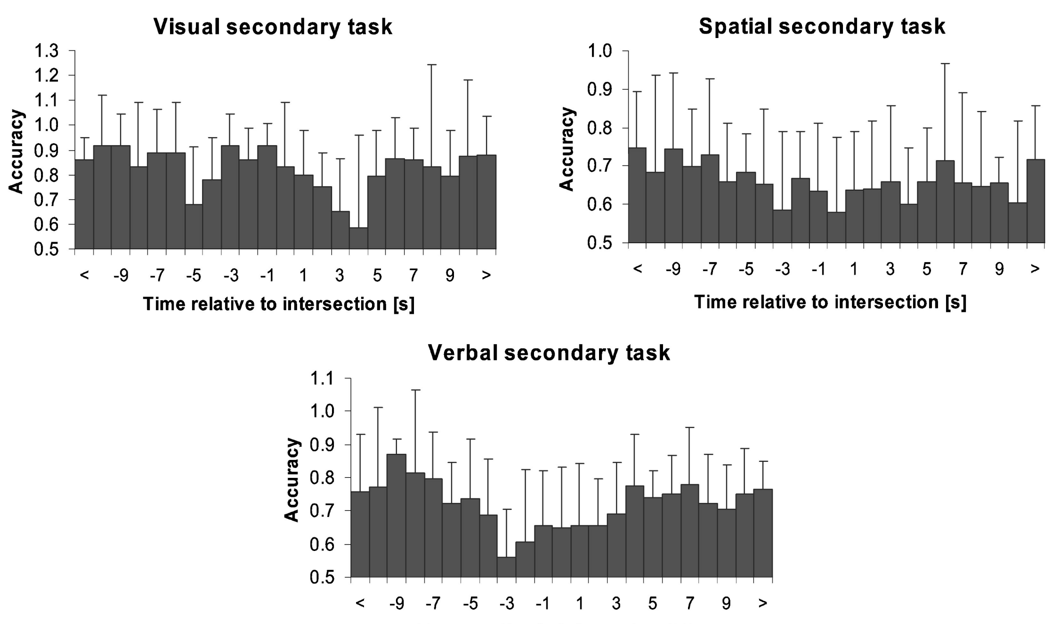

Fig. 7. Accuracy in the secondary tasks as a function of time relative to passing the middle of an intersection.

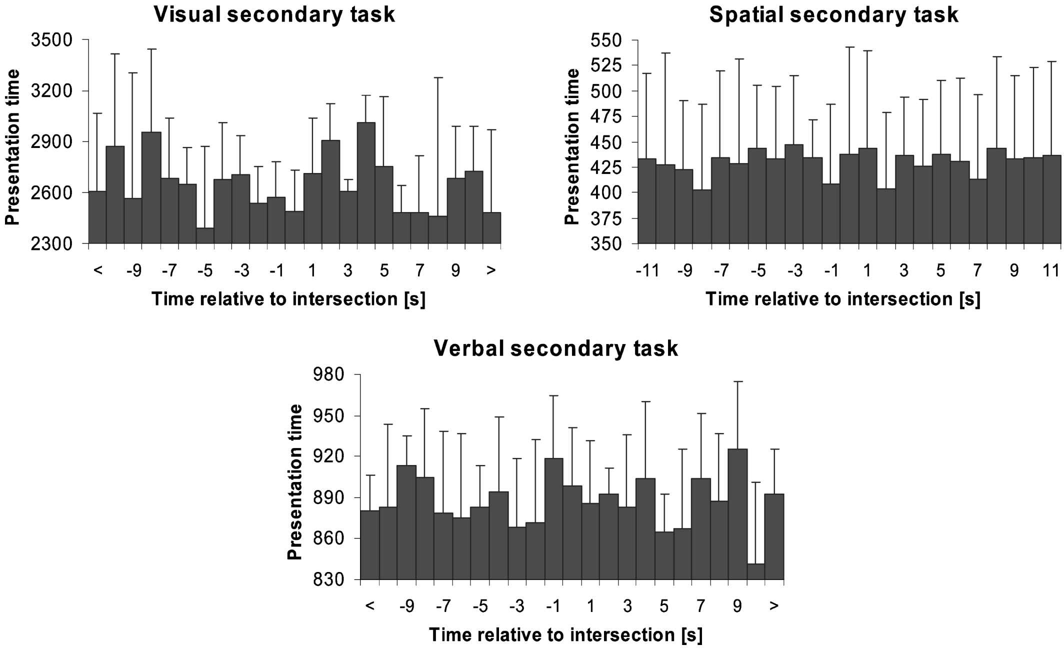

Fig. 8. Presentation time of the secondary tasks as a function of time relative to passing the middle of an intersection.

whereas these differences were not found for the other two secondary task conditions—verbal secondary task, $F(22, 110) = 1.99$, $p = .011$ ($\eta^2 = .28$); visual secondary task, $F(22, 110) = 1.37$, $p = .149$ ($\eta^2 = .21$); and spatial secondary task, $F(22, 110) = 1.24$, $p = .230$ ($\eta^2 = .20$). Overall, the interaction between secondary task and distance to an intersection was not significant: $F(44, 330) = 1.16$, $p = .233$ ($\eta^2 = .13$). Also, no effect was found for secondary task presentation time as a function of temporal distance to an intersection—visual secondary task, $F(20, 100) = 1.02$, $p = .447$ ($\eta^2 = .17$); spatial secondary task, $F(22, 110) = 0.59$, $p = .925$ ($\eta^2 = .11$); and verbal secondary task, $F(22, 110) = 1.0$, $p = .476$ ($\eta^2 = .17$; see Fig. 8). The accuracy and the presentation time of a secondary task also did not correlate with each other, excluding a speed–accuracy trade-off in the secondary tasks (see Fig. 9).

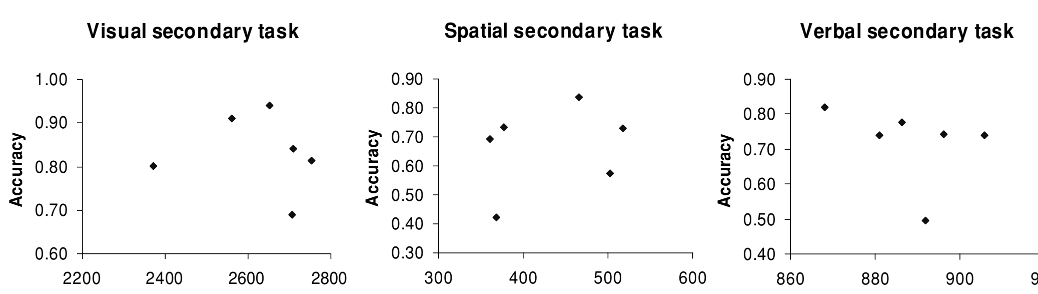

Fig. 9. Accuracy as a function of presentation time per participant for the three conditions with secondary tasks.

4. Discussion

The present study examined the working memory systems relevant for wayfinding. A verbal task put additional load on the PL. A visual and a spatial secondary task were used to put additional load on the VSSP, and to distinguish between the visual and spatial components of this subsystem. The main finding is that the verbal and the spatial secondary task interfered with wayfinding performance. First, they interfered compared to a control group. In contrast, the visual secondary tasks only had mild effects on wayfinding performance. Second, the verbal and the spatial secondary task also interfered more strongly than the visual secondary task.

Our findings indicate that both the PL and the VSSP in Baddeley's (1986, 2003; Baddeley & Hitch, 1974) working memory theory are involved in the encoding of environmental information used for wayfinding. The involvement of the PL indicates a kind of "verbal encoding," which might take the form of verbal directions like "left, then right, next left, straight, left," and so forth (cf. Couclelis, 1996; Daniel & Denis, 2004; Denis, 1997; Denis et al., 1999; Lovelace et al., 1999). In our experiment, producing such directions was inhibited by the verbal secondary task leading to worse performance during wayfinding. This interpretation is also supported by a questionnaire that had to be answered after the experiment. In this questionnaire, the verbal strategy of rehearsing route directions correlated highest with good wayfinding performance (*r* around .50).

The VSSP was also involved in wayfinding. However, it is a novel finding that an effect was found for the spatial, but not for the visual, secondary task (cf. Garden, Cornoldi, & Logie, 2002). Participants with the visual secondary task performed better than participants with the spatial secondary task. The spatial component of the VSSP seemed to be more important than the visual one. This points toward a higher importance for abstract spatial features like the geometry of an environment compared to mere visual surface features as proposed by Cheng (1986) and Gallistel (1990; see also Hermer & Spelke, 1994; Hermer-Vasquez, Spelke, & Katnelson, 1999; Learmonth, Nadel, & Newcombe, 2002; Wang & Spelke, 2002; this is discussed in more detail below). It also points against heavy reliance on pictorial information in the form of snapshots of the environment (Mallot & Gillner, 2000) or in the form of a map as seen from a birds-eye view (e.g., Kosslyn et al., 1978).

Is there an alternative interpretation of our findings? One might argue that the visual task required imagination, whereas the verbal and the spatial tasks were more perceptual in nature. Are our differences due to the fact that the visual secondary task was cognitively more demanding (i.e., requiring deeper, more complex, and more time-consuming processing)? We do not think that is a plausible explanation. If the visual secondary task required deeper processing, it should have also interfered more strongly with the deeper processing of wayfinding information. Usually, deeper processing is associated with better memory performance (e.g., Craik & Tulving, 1975). However, a stronger interference with deeper processing should lead to worse memory performance compared to other tasks, and not to better performance as was observed in learning while performing the visual secondary task.

Another possible interpretation is that the three secondary tasks did not load a single subsystem each, but rather had different visual, spatial, and verbal components. For instance, not only the spatial secondary task entailed spatial components. The visual secondary task also contained spatial aspects (i.e., the participants had to imagine a clock including watch hands that pointed in a specific direction, and they divided the imagined clock into an upper half and a lower half). Moreover, pressing buttons on a response box includes a spatial component, as either the left or the right button has to be pressed. The verbal task had the same problem. However, we do not think that these considerations present problems for our interpretations. First, the problem that a certain secondary task does not only put load only on the intended working memory subsystem, but also on other (unintended) subsystems, is a very general problem of the secondary task paradigm. All experiments in the paradigm have to deal with this problem (Gopher & Donchin, 1986). The visual secondary task might not load on an isolated system, but we think that it put much more load on the intended than on the unintended subsystem. In our experiment, we used secondary tasks that are very similar to the "standard tasks" of working memory research (e.g., Baddeley, 1986; Logie, 1995). A second support for our interpretation comes from earlier studies on human wayfinding. These studies also showed that environmental information is not encoded in one single memory system (i.e., representational format), and that wayfinders rely on spatial *and* verbal memory subsystems (Garden et al., 2002; Meilinger & Knauff, in press; Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000).

We believe that the most plausible interpretation of our findings is that wayfinding knowledge is not represented in a single format, but rather in two different but strongly interconnected formats. The root of this idea is in the innovative work by Paivio (e.g., Paivio, 1971). In the following, we propose a dual-coding theory of human wayfinding knowledge that is inspired by Paivio's (1971, 1986, 1991) theory.

The dual-coding theory of human wayfinding knowledge we are suggesting relies on the assumption that environmental information is encoded not only in a spatial format, but also in a verbal format. Our data suggest that during learning, the environmental information is encoded into a spatial format and, in addition, recoded into verbal directions like "second right." If an item must be retrieved from memory, it can directly activate a verbal or a spatial representation. However, the retrieval can also trigger references between the systems; the activation of a verbal memory trace can cross-activate an entity in the spatial system and vice versa. The account is supported by many findings. In wayfinding, Garden et al. (2002) found similar performance levels in participants who learned and retraced a route either during a spatial tapping or a verbal shadowing task. As in the present study, the dual-coding approach predicts encoding this route in a spatial and a verbal format. Equal interference levels are, therefore, expected. In wayfinding with maps and verbal directions, several studies found similar wayfinding performance for both wayfinding aids (Meilinger & Knauff, in press; Pazzaglia & De Beni, 2001; Schlender et al., 2000). According to the dual-coding approach, the participants, in addition, encoded the map in a verbal format showing verbal directions. If they also focused on these verbal directions, the similar performance levels for map instruction and verbal directions can be explained.

Paivio's (1971, 1986, 1991) original claim of dual coding was mainly about encoding verbally presented information in an additional visuo-spatial format. In the context of wayfinding, however, dual coding is the other way round. It is about encoding spatial information, in addition, in a verbal format. This relates to embodiment and to the grounding problem of how knowledge is connected to the world from which it is acquired and how it is then used in order to act. A spatial representation acquired while navigating through the world, or at least watching a video of a highly realistic city, is probably well-grounded. It is closely related to our perceptual input and probably can be used by an embodied agent for retracing a route without translating it into a more abstract propositional format and without having to rely on complex higher level cognitive processes. Most non-human animals are thought to navigate on this level. The dual-coding theory proposes that we, in addition, recode this spatial format into a verbal format. This involves further abstraction from the perceptual input. However, the spatial representation might also, in a sense, ground the verbal representation at a higher level.

A related account is the perceptual symbol system approach by Barsalou (1999; Barsalou, Simmons, Barbey, & Wilson, 2003). In this approach, a modality-specific conceptual system is assumed. However, such perceptual symbols alone do not seem to be sufficient to explain the results in our experiment because the verbal secondary task had a disrupting effect on wayfinding performance; and this indicates that a "non-perceptual," language-based, or propositional format may also be involved in human wayfinding (see also Garden et al., 2002; Hermer-Vasquez et al., 1999).

On a more general level, the combination of spatial and verbal encoding can also be found in other cognitive theories (e.g., Creem & Profit, 1998; Huttenlocher, Hedges, & Duncan, 1991; Kosslyn et al., 1989). These approaches typically differentiate between a categorical and a precise, more perception-based format. This latter format is always assumed to be more fine-grained than the categorical. It could be spatial, in general (Huttenlocher et al., 1991); based on a coordinate system (Kosslyn et al., 1989); or linked to action (Creem & Profit, 1998; cf., Goodale & Milner, 1992). The categorical system often remains rather unspecified. We would like to complement these theories by proposing that storing spatial information categorically often works simply by storing verbal descriptions like, "at the T-intersection" or "turn right," and so forth. Encoding spatial information verbally in this way can account for many biases found in spatial memory. For example, it may account for biases in the memory of locations (Fitting, Allen, & Wedell, 2007; Huttenlocher et al., 1991); biases in the angles of intersections (e.g., Tversky, 1981); and it may mediate grouping effects due to political, semantic, or conceptual similarities (e.g., Carbon & Leder, 2005; Hirtle & Mascolo, 1986).

The dual-coding theory is mainly concerned with memory, predicting better performance by using multiple memory systems and explaining biases due to categorical encoding. However, by representing spatial information verbally, this verbal representation is accessible again as an input to our reasoning (Clark, 2006). This allows for new ways to acquire conclusions about our spatial environment. For example, when turning right twice in a grid city, wayfinders might conclude that they are now walking back in the direction that they were coming from and, therefore, assume that they went the wrong way. They could come to that conclusion also based exclusively on their spatial or fine-grained representation (e.g., mentally simulating their former path while updating their original orientation). However, with verbal representations, they gain multiple options for reasoning that allows for much more flexibility, as well as individual preferences in strategy choice.

The dual-coding approach assumes additional verbal encoding of spatial information. Our findings also provide preliminary indications of when this might happen during the learning of the route. In accordance with studies indicating the relevance of decision points for wayfinding (e.g., Aginsky, Harris, Rensink, & Beusmans, 1997; Janzen, 2006) in our experiment, the accuracy in the verbal secondary task decreased when the participants were approaching an intersection. Apparently, the interference was strongest not in the middle of an intersection, but rather shortly before the participants were reaching a decision point. This might be the moment at which spatial and verbal information processing overlap. However, additional research is needed to find further evidence to support this idea.

The dual-coding approach can also provide an alternative interpretation for the empirical findings in reorientation experiments. In the reorientation literature, geometry is considered an important component (cf. Wang & Spelke, 2002). This notion supports the interpretation of the spatial component in our experiment as geometry. The debate in reorientation research, however, mainly focused on the question of whether language processes were necessary to combine geometric and feature information—in our terms, spatial and visual information—as proposed by Hermer-Vasquez et al. (1999; see also Wang & Spelke, 2002). For example, they showed that adults generally use both geometric and feature information unless they are disturbed by a verbal shadowing task, where they have to immediately repeat words from a text presented via headphones. This interference does not occur during clapping a rhythm or repeating syllables. The assumption that language is *necessary* for combining geometric and feature information, however, is questioned by the finding that primates, birds, and even fish are able to accomplish this (e.g., Gouteux, Thinus-Blanc, & Vauclair, 2001; Sovrano, Bisazza, & Vallortigara, 2002). Also, the shadowing effects of language do not occur when the adults receive a training trial and more explicit instructions (Ratkliff & Newcombe, 2005). Our dual-coding approach assumes spatial (geometric) and visual (feature) information to be *additionally* coded in verbal format. It can explain the usefulness of language, without assuming language to be necessary for reorientation. It also explains the boost in reorientation performance within children around the ages of 5 and 6 years regarding their emerging spatial language abilities (e.g., verbal expressions involving the terms "left" and "right"; Hermer-Vazquez, Moffett, & Munkholm, 2001; Learmonth et al., 2002). As mentioned earlier, such emerging verbal representations may be a new basis for children's reasoning about space and are grounded in corresponding visual or spatial representations.

The dual-coding theory also corresponds to representational accounts that originate mainly from robotics (Kuipers, 2000; Kuipers, Tecuci, & Stankiewicz, 2003). In the "spatial semantic hierarchy," Kuipers proposed multiple formats that represent a knowledge of large-scale spaces at different levels. Like in the dual-coding theory, qualitative and quantitative representations are assumed. The present experiment was concerned with the encoding of routes. This corresponds to the causal level in the spatial semantic hierarchy, where views and actions are represented. These views and actions are symbols that trigger dynamical control laws that themselves guide a navigator from one location to another. The views and actions can be qualitative symbols or continuous attributes. The latter is particularly relevant in the case of actions—for example, "turn 67°" or "walk 110 meters." This distinction is similar to the dual-coding theory. Verbal expressions like, "turn right at the church," are qualitative representations. However, continuous attributes like turn 67° are more likely represented spatially rather than verbally. Both the verbal and the spatial representations are able to trigger a specific motor representation or control law to act in space. Contrary to the verbal and spatial representations, the motor representations or control laws are not consciously accessible in humans. On a higher "topological" level of representation, the spatial semantic hierarchy assumes places, paths, and regions. Such elements are easy to represent verbally (e.g., "market place," "high street," or "downtown"), and can be used for planning. Using a hierarchical planning strategy of first planning the route to the goal region (e.g., Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2006; Wiener & Mallot, 2003), or to an important street, might lead to using mainly a skeleton of important streets that are identified verbally or are main connectors between regions (cf. Kuipers et al., 2003).

A possible disadvantage of our study is that our participants were placed in a virtual environment and also walked virtually, not physically. Various spatial orientation experiments have shown the importance of bodily cues available during walking (i.e., vestibular information especially during turns, proprioceptive information, and efference copies; Gale, Golledge, Pellegrino, & Doherty, 1990; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; but, see also Riecke, van Veen, & Bülthoff, 2002). In our experiment, participants could not use these cues, but had to rely explicitly on the simulation. It is possible that this is one reason that spatial and verbal memory systems were found to be more important than visual memory. We cannot rule out this criticism. However, this critique would apply to most experiments that use a virtual environment paradigm to merge high variable control and maximally realistic experimental conditions.

As Baddeley (2003) pointed out, little work has been done on the role of the VSSP in spatial orientation. This experiment is a small step toward changing this situation. On the one side, our results point toward a further differentiation of the VSSP into spatial and visual subsystems in the context of spatial orientation, with the spatial subsystem being involved more strongly. On the other side, our results highlight the involvement of the PL for spatial orientation. Although PL and VSSP might have developed for different demands posed from our environment, we seem to leverage both of them in order to solve our tasks in experimental situations as well as in daily life.

Note

1. No differences for the order of route presentation could be found: time, $t(22) = 0.18$, $p = .863$, $d = 0.037$; got lost, $t(22) = 0.32$, $p = .752$, $d = 0.065$; and stops, $t(16.7) = 0.46$, $p = .654$, $d = 0.094$). The data were collapsed across both orders for the further analysis.

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