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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. We show 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.

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 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 and/or spatial information, and the central executive which is described as a supervisor responsible for the coordination of the subsystems and the selection of appropriate reasoning and storage strategies (Baddeley, 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”, “at the church to the right”

(cf. Denis 1997), the wayfinding should involve resources of the PL and thus interfere with a verbal secondary task. If the wayfinding knowledge is represented and processed in 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 more on the visual component, the other one focused more on the spatial component of the VSSP. If the wayfinding knowledge is represented and processed in a “picture-like” format e.g., in a snapshot of the environment (Mallot & Gillner, 2000) or a map, 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 and processes, e.g., the geometric layout of an environment (Cheng, 1986; Gallistel, 1990), it should involve the spatial component and interfere with a spatial secondary tasks. The goal of the present paper is to test these competing hypotheses.

Methods

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 centre of Tübingen (see Figure 1). During this *learning phase* they 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. During this wayfinding phase a number of dependent measures were recorded. Secondary task performance was recorded during the learning phase. Note that the secondary task was applied to the learning and encoding phase and the performance measures were collected during the wayfinding, i.e. when the participants had to remember what they had learned in the learning phase. In this way we could measure to which degree the secondary task interfered with the encoding and maintenance of wayfinding knowledge, while the wayfinding itself was not disrupted by any secondary task.



Figure 1: A snapshot of Virtual Tübingen.

Participants

Twelve female and twelve male participants, mainly students between 19 and 32 ($M = 24$; $SD = 4$) participated in the experiment which took place in Tübingen. None of them had visited Tübingen before. In travelling to the experiment no part of Tübingen used in the experiment could be seen. 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.

Procedure, Apparatus, and Materials

The experiment was separated into two phases. In the *learning phase* the participants were acquainted with two routes (see below). In the *wayfinding phase* they had to walk these ways by using a joystick. In both phases, the participants were sat on a chair positioned 3.5 metres from a circular 220° screen (width: 13m, height: 3m), which covered the whole horizontal visual field (see Figure 2). A pc-cluster rendered the projection for an eye position 1.20 meter above the ground referring to average eye-height in when seated. The frame rate was 60Hz using 2 x hardware anti-aliasing and hardware soft-edge blending to display the images on the curved screen. Three projectors with a resolution of 1024 x 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.

Learning Phase In the learning phase the participants were passively carried on two routes through virtual Tübingen. The transportation speed was two metres per second corresponding to a fast walking speed. The two routes presented in Figure 3 were the same as those used in a previous study conducted in “Real Tübingen” (Meilinger, 2005; Meilinger & Knauff, submitted). The 120 m ‘long route’ consisted of ten mainly oblique intersections with 23 possible choices. With a length of 80 m the short route

consisted of nine mainly 90° intersections, with 21 possible choices (for further discussion of these routes see Meilinger & Knauff, submitted). Presentation of the long route took 240 seconds; the short route took 160 seconds. The order of presentation of the routes was controlled.

While the participants learned a route they were confronted with one of the secondary tasks. They were randomly assigned to one of four conditions: the verbal secondary task, the visual secondary task, the spatial secondary task and the control group where no secondary task had to be completed. This resulted in six participants per group. All three secondary tasks were presented via headphones with active noise cancellation. The participants had to respond by pressing a button on a response box.

In the *verbal task*, the participants had to perform a lexical-decision task. They had to decide whether a presented word existed in German or not. All 100 German nouns consisted of two syllables and were among the 10000 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 vocalisation.

In the *visual task* the participants heard times and had to imagine a clock with watch hands. E.g., at “six o’clock” the short watch hand points downwards, the long watch hand upwards. If the clock is divided in an upper and a lower half, both watch hands point into different halves. At “twelve o’clock” or “twenty past four” 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 five minutes were used e.g., 11:55 with times in the third or ninth 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 upwards or downwards. The resulting 100 times of day again were spoken by a television speaker, recorded



Figure 2: The experimental setup.

via microphone and cut into sound files with the start of the file matching the onset of the vocalisation. The participants were explicitly instructed to solve the tasks by imaging the clock.

In the *spatial task* the participants had to indicate the 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. The sound was spatialised 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 (HRTF). 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-subject pre tests, 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-subject pre-tests with 18 participants led to trial durations of 1.2 seconds in the verbal, 4 seconds in the visual and 0.8 seconds in the spatial task. The corresponding hit rates in the pre-tests were 86% for the verbal, 85% for the visual 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 accurate 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 seconds. This is the average of the 160 seconds for presenting the short route and the 240 seconds for presenting the long route. All secondary tasks were presented in random order with accuracy and reaction time recorded. For the visual and the verbal task the positions of the buttons were selected randomly for each participant. Prior to the baseline the participants trained the secondary task for several minutes.

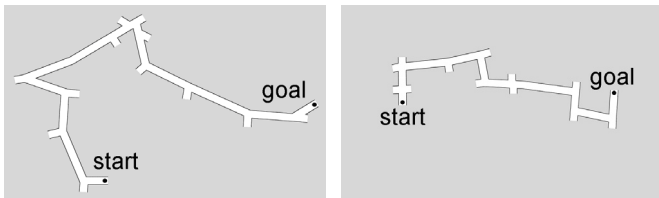


Figure 3: Maps of the long route (left) and the short route (right).

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 two metres 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 (1) the time from the first movement to reach the goal, (2) the traversed distance, (3) the number of stops and (4) the number incidents when participants got lost. Stops were counted if they at least lasted one second and if they started at least one second after a previous stop. A participant was considered to be lost when turning into a wrong street and hitting an invisible wall, which was located at about five meters after entering the wrong street. In this case the participant had to turn around. From these four parameters *getting lost* was the most important, because in real settings each incident of taking a wrong direction can result in a much longer distance and time to reach the goal or even in not reaching the goal at all. Distance and getting lost correlated by .89 ($n = 24, p < .001$). So 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. They navigated around in a small area of Virtual Tübingen not encountered during the rest of the experiment. This also included an invisible wall indicating a wrong choice of route later in the experiment.

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 ANOVAS for performance over both routes were computed followed by planned contrasts between the experimental groups. Additionally, t-tests accounted for differences due to gender, the order of routes and dependent differences between the two routes.

Wayfinding Performance

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

The main effect of secondary tasks on wayfinding performance is shown in Figure 4. The groups differed in their frequency of getting lost (ANOVA $F(3, 20) = 5.43, p = .007; \eta^2 = 0.45$). The 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. As seen in Figure 4 the verbal secondary task had a bigger influence than the visual

secondary task. This difference attained significance on the short 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 statistical 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 ($t(20) = 0.73, p = .476, d = 0.15$). 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.

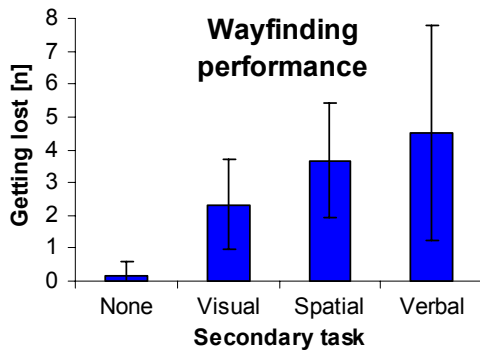


Figure 4: Getting lost per person on both routes as a function of the secondary task during encoding. Means and standard deviations are shown.

Secondary Task Performance

One possible explanation for our findings could be that the differences in the main tasks are only due to differences in the secondary tasks. To rule out this explanation we conducted a further analysis over the secondary tasks during learning. Overall, the three groups with secondary tasks did not differ in accuracy on the baseline measure taken before the main experiment (see left hand side of Figure 5; $F(2, 15) = 1.68, p = .220; \eta^2 = 0.18$). As in the pre-tests the secondary tasks were comparable with regard to their

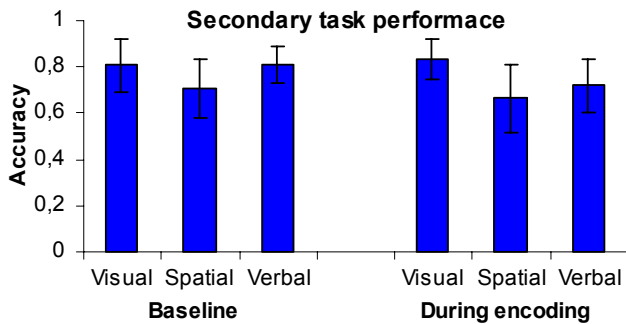


Figure 5: Accuracy in the secondary tasks during baseline (left) and during encoding of the routes the participants had to walk immediately afterwards (right).

difficulty. There was also no main effect of secondary task during encoding (see right hand side of Figure 5; $F(2, 15) = 3.12, p = .074; \eta^2 = 0.29$). No trade-off between main and secondary task, therefore, 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 task were found ($t(15) = 0.79, p = .444, d = 0.19$).

There was no gender effect in secondary task performance. Neither in the baseline ($t(16) = 1.51, p = .151, d = 0.36$) nor during encoding of the route ($t(16) = 0.90, p = .929, d = 0.21$). There was also no difference between the routes ($t(17) = 0.22, p = .829, d = 0.052$).

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 of the study 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 stronger than the visual secondary task. For the verbal secondary task this was found in wayfinding performance on the short route. For the spatial secondary task this was found in secondary task performance. These results cannot be explained by a performance shift between first and secondary task, as participants with the visual secondary task performed better in wayfinding *and* in the secondary task compared to participants with the verbal or the spatial secondary task.

So, what is the relation between human wayfinding and the modality specific systems in Baddeley's working memory theory? Overall, both the PL and the VSSP seem to be involved in the encoding of environmental information used for wayfinding. The involvement of the PL indicates that the wayfinders use a kind of "verbal encoding" when they learn a route. As Denis (1997) argued they might use verbal directions such as "next left", "at the church to the right". In our experiment, producing such directions is inhibited by the verbal secondary task leading to worse performance during wayfinding. Participants without verbal secondary task could use such verbal directions. This 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 ($n = 24$; getting lost: $r = .49, p = .016$; time: $r = .44, p = .034$; stops: $r = .55, p = .006$). The availability of various landmarks in our realistic setting might have eased encoding the routes verbally. However,

learning these routes from a map without landmark would also suggest verbal encoding (Meilinger & Knauff, submitted).

Not only the PL, but also the VSSP was 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 towards 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). It also points against heavy reliance on pictorial information in form of snapshots of the environment (Mallot & Gillner, 2000) or in form of a map as seen from birds eye view.

Our results show that environmental information is not encoded in one single memory system, i.e. representational format. The participants used spatial *and* verbal memory components for encoding wayfinding knowledge. These findings are in accordance with the assumption that similar representations are built from direct experience and textual descriptions (cf. Taylor & Tversky, 1992). The findings extend this position by showing that more than just one representation is involved. This fits nicely with the dual-coding approach of human wayfinding (Meilinger & Knauff, submitted). The account is inspired by Paivio's (1971) dual coding theory. It assumes that environmental information is encoded not only in visual or spatial format but also in verbal format. Our data suggests that during learning, the environmental information is at least in parts re-coded into verbal directions like "2nd right, at the church to the left". However, our findings also suggest that participants represent the environmental information in a non-verbal format, too. This representation primarily accounts for spatial information, while visual features of the environment seem to play only a marginal role in the corresponding mental representations. In the following we want to show that the dual coding approach of human wayfinding not only explains our data, but also fits nicely with many other findings reported in the literature on wayfinding and reorientation.

In wayfinding Garden et al. (2002) found similar performance levels in participants who learned and retraced a route either during a visuo-spatial or a verbal secondary 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 directions several studies found similar wayfinding performance for both wayfinding aids (Meilinger & Knauff, submitted; Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000). According to the dual-coding approach the participants additionally encoded the map in a verbal format that is verbal directions. If they also focused on these verbal directions, the similar

performance levels for map instruction and verbal directions can be explained.

In reorientation research the dual-coding approach can provide an alternative interpretation for the empirical findings. The debate 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, Spelke and Katsnelson (1999). 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 (Ratcliff & 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 five and six years regarding their emerging spatial language abilities e.g., verbal expressions involving the terms "left" and "right" (Hermer-Vasquez, Moffett & Munkholm, 2001; Learmonth, Nadel & Newcombe, 2002). Another recent explanation about this issue focuses on hemispheric crosstalk as a prerequisite for combining geometric and feature information (Newcombe, 2005). In the present form this approach does not explain why a verbal secondary task would inhibit hemispheric crosstalk as found in our experiment and by Hermer-Vasquez et al. (1999), whereas a visual secondary task or repeating only syllables would not inhibit hemispheric crosstalk.

The dual-coding approach can explain several results in our experiment and other areas of spatial orientation research. Are there alternative explanations for our results? Contrary to the pre-tests, the spatial secondary task showed a numerically higher difficulty than the baseline. The better performance in the visual compared to the spatial secondary task might therefore stem from a higher difficulty of the spatial secondary task and not from the higher importance of the spatial memory. This alternative explanation, however, does not contradict the dual-coding approach and it can not account for the importance of verbal memory.

We can not completely rule out that our effects were due to a different encoding strategy i.e. participants with a verbal secondary task were forced to rely on a potentially less efficient visual encoding strategy. In this case participants could, however, also rely on a spatial encoding strategy. With each secondary task the participants always could apply two alternative strategies. We think, therefore,

that a more consistent explanation of our results involves different memory systems. An open question remains whether an effect would be obtained when applying a motor secondary task e.g., finger tapping.

Another result of our experiment showed males to perform slightly better in wayfinding than females. This result is well in line with many in other experiments (for a recent review see Coluccia & Louse, 2004).

Conclusions

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 towards changing this situation. On the one side, our results point towards 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. The dual-coding approach aims to reflect this incorporation of both systems.

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