Viewing a Map Versus Reading a Description of a Map: Modality-Specific Encoding of Spatial Information

Michael Tlauka, Hannah Keage, C. Richard Clark

School of Psychology, Flinders University

Abstract

This study investigated whether brain neural activity that accompanied the processing of previously learned map information was influenced by the modality in which the spatial parameters of the maps were originally learned. Participants learned a map by either viewing it directly or by reading an equivalent verbal description. Following learning, the participants' ability to use their spatial knowledge was tested in a spatial orientation task. Electrophysiological recordings identified significant effects of prior learning modality on event-related brain activity within 300 ms following the presentation of map orientation instructions. The results indicate that modality-specificity in spatial memory is present at a very early stage of processing.

Keywords: Mental representation; Spatial cognition; Situation model; Modality; Vision; Language; Neural activity

Mobile organisms rely on their ability to learn and remember the spatial location of objects in the environment. In humans, spatial information is predominantly received from two types of input channels or modalities, vision and language. When reading text or listening to spoken conversations, people construct what has come to be known as situation (mental) models (Johnson-Laird, 1983). Situation models are generally assumed to represent linguistic information at a level that is deeper than verbatim surface representations, providing an understanding of the state of affairs of the presented material. This is achieved through the integration of new information into preexisting knowledge structures.

Several theorists have advocated the notion of a common format of spatial information. For example, Bryant (1992) argued that there is a spatial cognitive system that is independent of other forms of knowledge. Different sources such as visual and linguistic inputs provide information that is used to build modality-independent spatial models. In a similar vein, Jackendoff

and Landau (1991) emphasized that representations underlying spatial knowledge are modality-independent (see also Clark, 1973; Jackendoff, 1987; Levelt, 1984; Miller & Johnson-Laird, 1976). Other researchers, though, have argued for multiple levels of encoding that include text-based representations as well as situation models that are integrated with preexisting knowledge (Fletcher & Chrysler, 1990; Mani & Johnson-Laird, 1982; Schmalhofer & Glavanov, 1986; van Dijk & Kintsch, 1983).

This study examines whether visuospatially (e.g., looking at a map) and verbally (e.g., reading a description of a map) acquired spatial memories are similar. More specifically, the aim of this study is to determine whether spatial representations in humans are modality independent or modality specific. Modality independence implies that following the perceptual encoding of the material, the information is processed in a common (shared) spatial system (Bryant, 1992). In other words, the same representational system handles all types of input, irrespective of modality. In contrast, modality specificity implies that visual and verbal information are processed by specialized spatial systems such that verbal material is processed by a verbal spatial system, whereas visual information is processed by a visual spatial system.

1. Cognitive–behavioral and psychophysiological evidence

There is behavioral evidence demonstrating that visuospatially and verbally acquired spatial memories are comparable in many respects. Scanning paradigms have shown that it takes more time to scan mentally a longer than a shorter path when learning is based on text (Denis & Cocude, 1989), replicating studies of visuospatially based materials (Kosslyn, Ball, & Reiser, 1978). Oakhill and Johnson-Laird (1984) found that visuospatial tracking could interfere with the processing of verbal material, suggesting a common format for encoding.

However, discrepancies in the underlying representations have also been reported. Learning from maps has been shown to be faster than learning from linguistic inputs (Denis & Zimmer, 1992). Franklin (1996) argued that memories for described scenes are not as rich in metric information (e.g., route length, angles at which routes join) by comparison with memories acquired through primary experience.

Independent investigations into the neural bases of visual perception and verbal encoding have revealed that both involve similar neural substrates (see Mazoyer, Tzourio-Mazoyer, Mazard, Denis, & Mellet, 2002, for a summary). Using a PET scan, Mellet et al. (2002) found that mental scanning based on visual perception and verbal descriptions activated parieto-frontal networks. Interestingly, differences were also observed, with an involvement of the right medial temporal lobe following visually based learning, whereas verbal learning resulted in an activation of the language areas (see also Mellet et al., 2000).

To summarize, some of the findings from the behavioral and PET studies are consistent with the notion of integration into a similar format of representation. However, important differences in the areas activated (such as medial temporal lobe involvement following visuospatial learning only) indicate that spatial models retain modality-specific information. To further examine these differences, this study focuses on the *temporal* characteristics of the brain events involved in processing orienting instructions relative to maps learned from either verbal or visuospatial information. Although PET studies are appropriate for indicating the brain areas

mediating information processing, PET, a measure of hemodynamic activity, does not have the temporal resolution for discriminating between temporally rapid events, such as are likely to occur during spatial encoding, and spatial information processing.

2. This study

Employing both behavioral and psychophysiological measurements, this investigation examines whether modality-specific differences in the encoding of map orienting instructions are present early in processing (less than 300 msec poststimulus onset). Participants either viewed a map (Fig. 1) or read an equivalent description of the map. Subsequently, participants' ability to use the spatial knowledge they had acquired was tested, employing a spatial orientation task during which EEG activity was recorded. By averaging EEG time-locked to the onset of specific task stimuli, it was possible to derive measures of brain activity that reflected the processing of the orientation stimuli (termed *event-related potentials* or ERPs) with millisecond resolution. Brain activity related to the processing of spatial information was inferred from the amplitude, latency, and topography of a number of spatiotemporal components of the ERP. *Amplitude* specifies the degree of activation of related brain structures, *latency* refers to the time course to peak of such activity, and *topography* approximates the brain regions involved.

The electrophysiological analyses employed in this investigation focus on the early ERP components (P1, N1, and P2) that are obtained within 300 msec poststimulus over occipital, temporal, parietal and frontal regions. These early components have been shown to mark the preconscious stages of processing associated with the detection and assimilation by the brain of a stimulus event (Hillyard, Teder-Salejarvi, & Munte, 1998). In this study, these components were obtained to map orientation stimuli and used to identify similarities and differences in brain activity that are the result of earlier vision-based and language-based learning of map
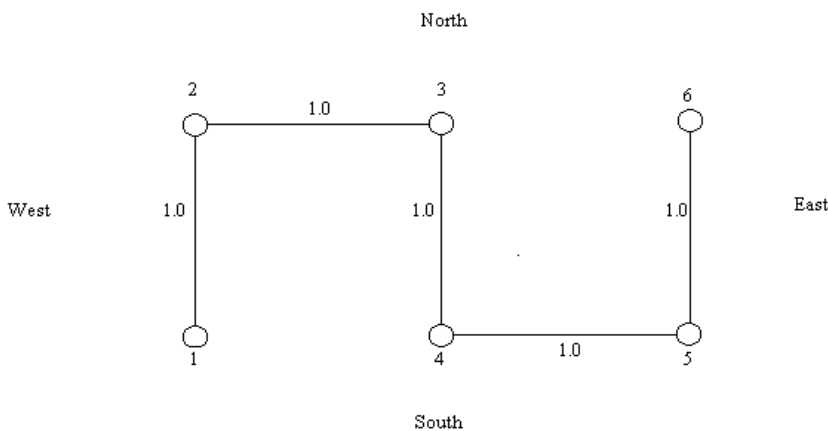

Fig. 1. One of the maps presented to participants in the visuospatial learning group.

parameters. The inclusion of behavioral measures allowed us to examine the important relation between behavioral responses and underlying brain activity.

3. Method

3.1. Participants

Thirty-six female university students with a mean age of 21 years (range: 18–38 years) and an average of 13 years of education (range: 10–15 years) participated in the study. All reported English as their first language and were assessed to be strongly right-handed (Annett, 1970). Participants were randomly allocated to two map learning groups: visuospatial and verbal.

3.2. Materials

The experiment consisted of a learning phase followed by a test phase. In the learning phase, participants in the visuospatial learning group studied one of two maps. The maps consisted of a simple route, with six points joining five segments. One of the maps is shown in Fig. 1. The other map was a mirror image of the one shown in Fig. 1. The verbal learning group was presented with corresponding verbal descriptions of the maps. The description of the map shown in Fig. 1 was as follows:

The first path starts at Point 1 and extends 1.0 m northward to Point 2.
The second path starts at Point 2 and extends 1.0 m eastward to Point 3.
The third path starts at Point 3 and extends 1.0 m southward to Point 4.
The fourth path starts at Point 4 and extends 1.0 m eastward to Point 5.
The fifth path starts at Point 5 and extends 1.0 m northward to Point 6.

The maps and the verbal descriptions were presented 40 cm vertically ahead at eye level on cardboard (approximately 20 cm × 15 cm). In the test phase (during EEG data collection), all stimuli were presented in white on the black background of a PC monitor (14 inches). Viewing distance was approximately 90 cm. Participants responded to orientation and direction probes by pressing specified buttons on a response box.

3.3. Procedure

Participants were tested individually. In the learning phase, half of the participants in the visuospatial learning group studied one map, with the remaining students studying the alternative map. Presentation of the map descriptions was similarly counterbalanced in the verbal learning group. An EEG cap was fitted while participants were presented with the relevant material (approximate study time: 20 min).

Following learning, the map or description was removed and the test phase began. On 64 trials, participants' knowledge of the maps or descriptions was tested as follows: Each trial started with the presentation of an outline of a rectangle displayed on the PC monitor. After a delay of 1,000 msec, an orienting instruction was presented within the rectangle for 400 msec.

The orienting instruction consisted of a set of four symbols defining a location (either Point 3 or Point 4; see Fig. 1) and an orientation on the map (facing north or south). For example, the instruction 4/3A instructed the participant to imagine herself at Location 4 on the map, with Location 3 being ahead. Note that prior to the test phase, participants were trained to interpret the orienting instructions.

Participants were required to press a specified button on the response box as soon as they had a mental image of the orientation. At 3,600 msec following the onset of the orienting instruction, a probe stimulus was displayed within the rectangle for 400 msec. Probe stimuli were numerals that indicated locations on the map that were to the left or right relative to Locations 3 and 4 (Points 1, 2, 5, and 6). Participants responded by pressing one of two buttons indicating the direction of the target object (left or right) relative to their imagined orientation. Recording participants' responses allowed the identification of trials with no or incorrect responses. A black screen was then presented for 1,000 msec prior to the onset of the next trial.

3.4. Electrophysiological data acquisition

The EEG was recorded via 19 tin electrodes (see Fig. 2) referenced to a single noncephalic electrode on the left ear according to the International 10/20 System: frontal (FP1, FP2, FZ, F7, F3, F4, F8), central (CZ, C3, C4), temporal (T3, T5, T4, T6), parietal (PZ, P3, P4), and occipital (O1, O2). Electrodes were part of an elasticized cap (Electro-Cap International, Eaton, Ohio) and were filled with Electro-Gel (Electro-Cap International). EEG data were time-locked to the onset of the orienting instructions. Eye movements and blink artifacts were monitored by electrooculogram, recorded using electrodes on the outer canthus of the right eye and external canthus of the left eye, and vertically above and below the left eye. Electrode im-
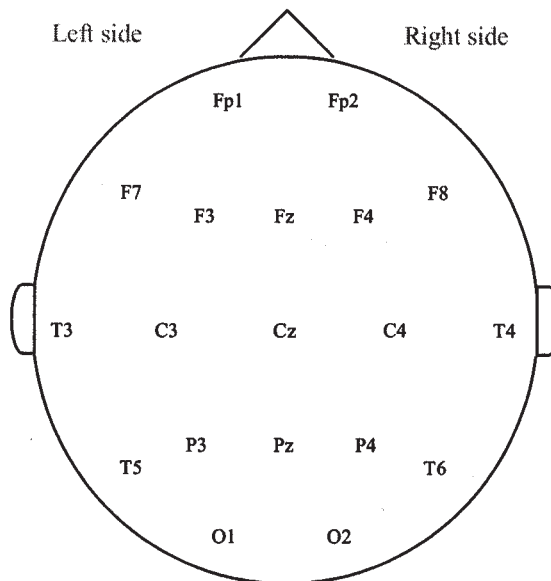

Fig. 2. Electrode placement. Figure adapted from Jasper (1958).

pedance was kept below 10 kOhms. Electrophysiological data were acquired continuously by a SYNAMPS system with ESI-128 software (Neuroscan, El Paso, Texas) at a sampling rate of 500 Hz. These analog EEG data were amplified across a bandpass of DC-100 Hz with 16-bit resolution.

3.5. Data analysis

Each participant's electrophysiological data were individually inspected for muscular activity, and time periods whereby these activities excessively disturbed the EEG were excluded. Ocular artifacts were corrected offline. Using behavioral data, trials where the participant responded incorrectly or not at all were excluded. EEG data were then epoched between –100 to 400 msec relative to stimulus onset, baselined on the prestimulus interval, and averaged according to learning group (verbal, visuospatial) and alignment instruction (north, south).

Neuroscan software was employed to measure amplitudes and latencies of the P1, N1, and P2 components for each individual participant's ERPs. The P1 and N1 components are generally measured over occipitotemporal scalp sites and are associated with stimulus processing associated with determination of stimulus relevance, an effect moderated by the brain's attentional control systems, and with related, high-level categorization (Antal, Keri, Kovacs, Janka, & Benedek, 2000; Hillyard et al., 1998; Thorpe, Fize, & Marlot, 1996). The P2 component is also measured over occipitotemporal regions, although a positive component at about the same latency can be observed over frontal regions, and reflects postattentional decision processes concerning stimulus encoding, prior to integration within the ongoing working memory context induced by tasks and goals (Anllo-Vento, Luck, & Hillyard, 1998; Hillyard et al., 1998). Amplitude and latency values from each participant were averaged according to learning group and orientation.

4. Results

4.1. EEG data

Mixed analyses of variance were performed on the mean amplitudes and latencies of the P1, N1, and P2 components. The EEG data were analyzed at sites of predicted effects. The analyses of variance included learning group (verbal, visuospatial) as a between-subject factor, and orientation (north or south facing) and hemisphere (left, right) as within-subjects factors. Only the main findings involving learning group and alignment are reported here.

4.2. P1 amplitude and latency

Occipitotemporal (T5/T6) electrodes were included in P1 analyses. The P1 amplitude analyses revealed no significant main effects or interactions with learning group ($ps > .05$). With respect to P1 latency, the main effect of learning group, $F(1, 34) = 10.50, p < .01$, and the interaction between alignment and learning group were significant, $F(1, 34) = 11.56, p < .01$. Independent t tests (with Bonferroni correction here and in all subsequent post hoc comparisons)

indicated that the visual group (99 msec ± 11 msec) displayed significantly slower latencies than the verbal group (86 msec ± 9 msec) on north-facing trials, whereas the corresponding difference on south-facing trials was not significant (visual group 90 msec ± 11 msec; verbal group 88 msec ± 9 msec).

4.3. N1 amplitude and latency

Occipital (O1/O2) and occipitotemporal (T5/T6) electrodes were included in the N1 analyses. Analysis of N1 amplitude revealed a significant interaction between hemisphere, electrode, and learning group, $F(1, 34) = 7.86$, $p < .01$, as displayed in Fig. 3. In the visuospatial learning group, the amplitude of the N1 component as measured at occipitotemporal electrodes was more negative in the right than the left hemisphere, whereas the difference between the hemispheres was not significant in the verbal learning group. There were no statistically reliable differences between the learning groups at occipital electrodes. The significant interaction between learning group and alignment, $F(1, 34) = 6.18$, $p < .02$, was due to the verbal group (–8.84 mv ± 5.07 mv) displaying significantly greater amplitude than the visual group (–5.77 mv ± 4.52 mv) on south-facing trials, but there were no significant differences on north-facing trials (visual group: –9.21 mv ± 5.39 mv; verbal group: –8.87 mv ± 4.86 mv).

Analysis of N1 latency indicated a significant interaction between electrode and learning group, $F(1, 34) = 5.29$, $p < .03$. The visuospatial group displayed significantly longer latencies than the verbal group at occipital electrodes ($p < .05$), as shown in Fig. 4. The corresponding differences at occipito-temporal electrodes were not significant ($p > .05$).

4.4. Frontal P2 amplitude and latency

Prefrontal (Fp1/Fp2), frontal (F3/F4) and frontotemporal (F7/F8) electrodes were included in frontal P2 analyses. There were no main effects or interactions with learning group for frontal P2 amplitude (ps > .05). However, the interaction between hemisphere, electrode, and alignment was found to be significant, $F(2, 68) = 22.94$, $p < .001$. There was more activity over the right prefrontal area (8.43 mv ± 5.17 mv) than the left prefrontal area (3.08 mv ± 7.70 mv)
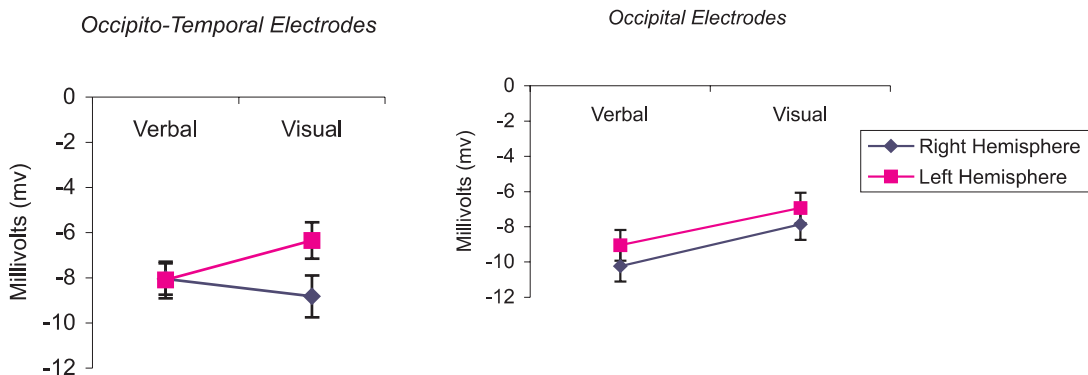

Fig. 3. N1 amplitude as a function of hemisphere, electrode and learning group. Error bars represent ± 1 estimated standard error of the mean.
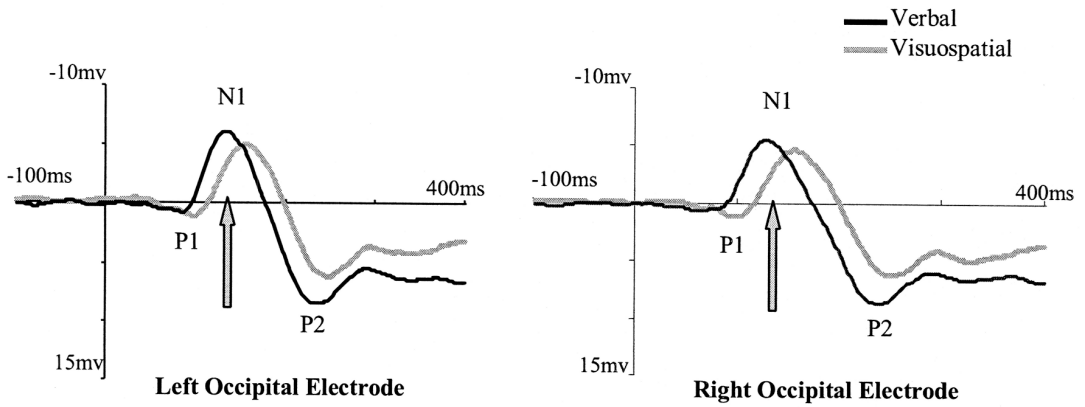
Fig. 4. N1 latency at occipital electrodes. The differences in latency between the visuospatial learning group and the verbal learning group are indicated by the arrows.

on south-facing trials. All other differences between the left and right hemispheres on north- and south-facing trials did not approach significance.

Similarly, analysis of P2 latency revealed a significant interaction between hemisphere, electrode, and alignment, $F(2, 68) = 10.20$, $p < .001$. There were longer latencies over the right prefrontal area (242 msec ± 36 msec) than the left prefrontal area (227 msec ± 37 msec) on south-facing trials. Further, the interaction between hemisphere and learning group was statistically reliable, $F(1, 34) = 6.83$, $p < .02$, which is displayed in Fig. 5. In the verbal learning group, the right hemisphere displayed a significant longer latency than the left, whereas the difference between the hemispheres did not approach significance in the visuospatial learning group.

4.5. Posterior P2 amplitude and latency

Occipital (O1/O2), parietal (P3/P4), and occipitotemporal (T5/T6) electrodes were included in posterior P2 analyses. Posterior P2 amplitude and latency analyses revealed no main effects or interactions with learning group ($ps > .05$).
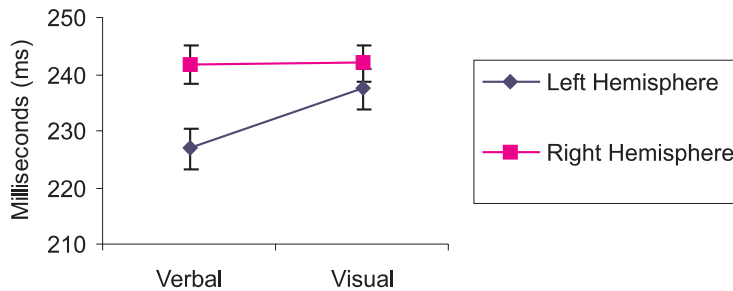

Fig. 5. Frontal P2 latency as a function of hemisphere and learning group. Error bars represent ± 1 estimated standard error of the mean.

4.6. Behavioral data

Reaction times to the orienting instructions and error rates (4.85% of all trials) for target localization were analyzed separately. The analyses revealed no significant effects involving learning group ($ps > .05$). Response times in the visuospatial group (1.70 sec $\pm$ 0.60 sec) did not differ significantly from those in the verbal group (1.60 sec $\pm$ 0.40 sec). Similarly, response errors in the visuospatial group (5.10% $\pm$ 5.00%) were not different from those in the verbal group (4.60% $\pm$ 3.40%). Performance was faster on north-facing trials (1.60 sec $\pm$ .52 sec) by comparison with south-facing trials (1.69 sec $\pm$ .51 sec), $F(1, 34) = 20.51$, $p < .001$. Further, there were fewer response errors on north-facing trials (3.73% $\pm$ 2.95%) than south-facing trials (6.25% $\pm$ 5.52%), $F(1, 34) = 9.31$, $p < .01$.

5. Discussion

Using behavioral as well as electrophysiological measurements, this study investigated whether visuospatial and verbal memories have a common format. Analyses of the behavioral data revealed no consistent effect of map learning condition on performance: There were no significant differences between the learning groups (a) in terms of reaction times to the orienting instructions and (b) in terms of response errors when identifying the direction (left or right) of the target objects. The behavioral data indicate that the level of learning in both learning groups was comparable. However, the pattern of neural activity recorded while participants performed the orientation task was affected by the modality in which the map was learned: On north-facing trials, P1 latency was faster at occipitotemporal electrodes (for both hemispheres) in the verbal learning group. N1 amplitude was stronger at the right occipitotemporal electrode in the visuospatial learning group, and there was stronger activation (for both occipital and occipitotemporal electrodes) in the verbal learning group on south-facing trials. N1 latency for the verbal learning group was shorter in both hemispheres at occipital electrodes. P2 latency was faster at the left frontal electrode in the verbal learning group.

Our findings show that by varying the modality of map learning, the latency, amplitude, and scalp topography of a number of ERP components to a given spatial memory probe changed in a reliable way. As the modality of learning during the learning phase was the *only* difference between the learning groups at any stage of the experiment, the results indicate important differences in the biological conformation of the underlying spatial memory as a function of learning modality.

The involvement of the right hemisphere in the processing of the maps (see N1 amplitude) supports earlier results by Mellet et al. (2002) who found that the right medial temporal lobe was involved following visually based learning. The novel aspect of this experiment is its focus on the early ERP components (P1, N1, and P2) that are obtained within 300 msec poststimulus over occipital, temporal, parietal, and frontal regions. Our results confirm that spatial processing is modality specific. More important, the findings further indicate that modality-specific representations are present at the very early stages of processing, which have been associated with the physical detection by the brain of a stimulus event (Hillyard et al., 1998).

It has been suggested that when acquiring spatial knowledge from verbal descriptions, people retain a verbatim surface representation of the text (i.e., the word-for-word details of sentences are encoded) and also the ability to construct a mental (situation) model (Mani & Johnson-Laird, 1982; van Dijk & Kintsch, 1983). Situation models differ from surface representations in that they provide an understanding of the spatial layout of the landmarks and locations described in the verbal material. Overall, performance in the verbal learning group may have involved a verbatim surface representation, a situation model, or a combination of both types of representation. These results do not allow us to distinguish between these alternatives.

Although modality-independent models of spatial representation can account for findings indicating that visual perception and verbal encoding both involve similar neural substrates (see Mazoyer et al., 2002, for a summary), they are inconsistent with earlier PET studies showing that spatial models retain some modality-specific information (Mellet et al., 2002). This type of model is also not in agreement with the significant effects of prior learning modality on event-related brain activity that were obtained in this investigation. This and earlier findings cannot exclude the possibility that some information may be retained in a modality-independent format, and hybrid models consisting of both modality-independent and modality-specific components may prove to be a viable alternative. At present, we do not know whether spatial representations can consist of modality-specific as well as modality-independent processes. However, on balance, the results from this study and those from earlier investigations (Mellet et al., 2002) do not support models of spatial representation that postulate a single modality-independent spatial system.

How does modality specificity relate to our finding that verbally encoded and visuospatially encoded spatial memories resulted in similar *performance* as indicated by the absence of any significant differences in the analyses of the behavioral data? Note that previous studies have also shown similarities in performance. For example, studies of mental scanning based on text (Denis & Cocude, 1989) have replicated findings employing visuospatially based materials (Kosslyn et al., 1978). Further, the categorical spatial task (pressing a button in response to orienting instructions) in this study led to similar behavioral alignment effects observed in tasks requiring precision—for example, pointing tasks (Valiquette, McNamara, & Smith, 2003). Finally, the maps presented to participants in this study were similar in complexity to those employed in related research (e.g., Denis, Goncalves, & Memmi, 1995).

Although in this study overall performance remained unaffected by prior learning modality, more important, the neural activity underlying the processing of the stimuli was influenced by whether a physical map or a text description of the map formed the basis of the spatial representations. The conflicting results derived from the behavioral and neurophysiological measures suggest that adopting particular orientations in imagined space can involve different patterns of brain activation. It is therefore important to include both behavioral and neurophysiological measures in studies examining the modality specificity of spatial memory.

In conclusion, the patterns of neural activity associated with the processing of map orienting information was found to depend on the modality in which the map was learned. For example, there was stronger right hemisphere than left hemisphere activation in those who originally learned map information visuospatially, whereas latencies for the verbal learning group were faster over occipital areas than the corresponding latencies for the visuospatial learning group. These findings indicate that modality specificity in spatial memory is present at a very early

stage of processing as evidenced in differences in the early components of brain event-related electrical activity.

References

Anllo-Vento, L., Luck, S., & Hillyard, S. (1998). Spatio-temporal dynamics of attention to color: Evidence from human electrophysiology. *Human Brain Mapping, 6,* 216–238.

Annett, M. (1970). A classification of hand preference by association analysis. *British Journal of Psychology, 61,* 303–321.

Antal, A., Keri, S., Kovacs, G., Janka, Z., & Benedek, G. (2000). Early and late components of visual categorization: An event-related potential study. *Cognitive Brain Research, 9,* 117–119.

Bryant, D. J. (1992). A spatial representation system in humans. *Psycoloquy, 3*(16), space 1.

Clark, H. H. (1973). Space, time, semantics and the child. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* (pp. 27–63). New York: Academic.

Denis, M., & Cocude, M. (1989). Scanning visual images generated from verbal descriptions. *European Journal of Cognitive Psychology, 1,* 293–307.

Denis, M., Goncalves, M.-R., & Memmi, D. (1995). Mental scanning of visual images generated from verbal descriptions: Towards a model of image accuracy. *Neuropsychologia, 33,* 1511–1530.

Denis, M., & Zimmer, H. D. (1992). Analog properties of cognitive maps constructed from verbal descriptions. *Psychological Research, 54,* 286–298.

Fletcher, C. R., & Chrysler, S. T. (1990). Surface forms, textbases, and situation models: Recognition memory for three types of textual information. *Discourse Processes, 13,* 175–190.

Franklin, N. (1996). Language as a means of constructing and conveying cognitive maps. In J. Portugali (Ed.), *The construction of cognitive maps* (pp. 275–295). Netherlands: Kluwer Academic.

Hillyard, S. A., Teder-Salejarvi, W. A., & Munte, T. F. (1998). Temporal dynamics of early perceptual processing. *Current Opinion in Neurobiology, 8,* 202–210.

Jackendoff, R. (1987). *Consciousness and the computational mind.* Cambridge, MA: MIT Press.

Jackendoff, R., & Landau, B. (1991). Spatial language and spatial cognition. In D. J. Napoli & J. A. Kegl (Eds.), *Bridges between psychology and linguistics: A Swarthmore festschrift for Lida Gleitman* (pp. 145–169). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Jasper, H. H. (1958). The ten twenty electrode system of the international federation. *Electroencephalography and Clinical Neurophysiology, 10,* 371–375.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness.* Cambridge, MA: Harvard University Press.

Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 47–60.

Levelt, W. J. M. (1984). Some perceptual limitations on talking about space. In A. J. van Doorn, W. A. van de Grind, & J. J. Koenderink (Eds.), *Limits in perception* (pp. 328–358). Utrecht, The Netherlands: VNU Science Press.

Mani, K., & Johnson-Laird, P. N. (1982). The mental representation of spatial descriptions. *Memory and Cognition, 10,* 181–287.

Mazoyer, B., Tzourio-Mazoyer, N., Mazard, A., Denis, M., & Mellet, E. (2002). Neural bases of image and language interactions. *International Journal of Psychology, 37,* 204–208.

Mellet, E., Bricogne, S., Crivello, F., Mazoyer, B., Denis, M., & Tzourio-Mazoyer, N. (2002). Neural basis of mental scanning of a topographic representation built from a text. *Cerebral Cortex, 12,* 1322–1330.

Mellet, E., Tzourio-Mazoyer, N., Bricogne, S., Mazoyer, B., Kosslyn, S. M., & Denis, M. (2000). Functional anatomy of high-resolution visual mental imagery. *Journal of Cognitive Neuroscience, 12,* 98–109.

Miller, G. A., & Johnson-Laird, P. N. (1976). *Language and perception.* Cambridge, MA: Harvard University Press.

Oakhill, J. V., & Johnson-Laird, P. N. (1984). Representation of spatial descriptions in working memory. *Current Psychological Research and Reviews, 3,* 52–62.

Schmalhofer, F., & Glavanov, D. (1986). Three components of understanding a programmer's manual: Verbatim, propositional, and situational representations. *Journal of Memory and Language, 25,* 279–294.

Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature, 381,* 520–522.

Valiquette, C. M., McNamara, T. P., & Smith, K. (2003). Locomotion, incidental learning, and the selection of spatial reference systems. *Memory & Cognition, 31,* 479–489.

Van Dijk, T. A., & Kintsch, W. (1983). *Strategies of discourse comprehension.* New York: Academic.