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Conditional reasoning with a spatial content requires visuo-spatial working memory

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In previous research, Toms, Morris, and Ward (1993) have shown that conditional reasoning is impaired by a concurrent task calling on executive functions but not by concurrent tasks that load on the slave systems of the working memory system as conceptualised by Baddeley and Hitch (1974). The present article replicates and extends this previous work by studying problems based on spatial as well as nonspatial relations. In the study 42 participants solved 16 types of spatial or nonspatial problems, both in a single-task condition and under concurrent matrix tapping, a task loading the visuo-spatial sketch pad. The findings were consistent with those of Toms et al. (1993) for problems with a nonspatial content. However, when the content was spatial, and only then, a dual-task impairment was observed: processing time of the first premise was lengthened, especially for problems with negations in the antecedent term, the consequent term, or both; moreover, the number of correctly solved problems with negations in both terms was smaller. The implications of these findings for the mental models theory and the mental logic theory are discussed.

During the last 10 years, several research groups have studied the involvement of the components of working memory in reasoning tasks. Following this line of research, the aim of the present article is to investigate the role of visuo-spatial working memory in conditional reasoning with a spatial content. According to Baddeley and Hitch (1974), the short-term working memory system consists of a number of slave systems controlled by a supervisory module, the central executive. Thus far, evidence has been accumulated in favour of the view that there are two functionally distinct slave systems. One of these is a phonological

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loop consisting of a store that maintains phonological information active during about 2 seconds and an articulatory loop that refreshes the information in the store (for an overview, see e.g., Baddeley, 1986). The other slave system is the so-called visuo-spatial sketch pad (VSSP) that is specialised to maintain visuo-spatial information for short periods of time (for an overview, see e.g., Logie, 1995). The central executive supervises the processing by the slave systems and is thought to be involved in any controlled task. Because reasoning requires such control, it is expected that loading a working memory system like the central executive with a concurrent task impairs reasoning performance. This expectation has been confirmed in all the dual-task studies of reasoning published thus far (see Gilhooly, Logie, Wetherick, & Wynn, 1993; Gilhooly, Logie, & Wynn, 1999; Klauer, Stegmaier, & Meiser, 1997; Meiser, Klauer, & Naumer, 2001; Toms et al., 1993; Vandierendonck & De Vooght, 1997), and is not at issue in the present article.

Theories, expectations, and findings are less consistent with respect to the involvement of other components (slave systems, in Baddeley's terminology) of working memory in reasoning. Gilhooly et al. (1993), for example, found no involvement of the slave systems in syllogistic reasoning with an abstract content (e.g., "all of the Xs are Ys"; "Z is an X"; Therefore?), except for some occasional impairment in the phonological subsystem. Vandierendonck and De Vooght (1997), on the other hand, studied meaningful linear syllogisms and found that a concurrent load on visuo-spatial working memory slowed the processing of the problem information, while solution accuracy depended on all three components of the working memory system. Note that this pattern of effects was found for both temporal (e.g., "Stan went to Paris before Pete did"; "Pete went to Paris before Ann did"; "when did Stan go to Paris relative to Ann?") and spatial (e.g., "the guitar is to the left of violin"; "the violin is to the left of the piano"; "where is the piano relative to the guitar?") linear syllogisms. Independently, Klauer et al. (1997) found similar effects in analogous spatial syllogistic reasoning tasks. More recently, Gilhooly et al. (1999) have also found that syllogistic reasoning with an abstract content was disrupted by a dual task (the presentation of unattended pictures) loading the imagery component of the VSSP. However, this effect was only found in highly skilled participants. In addition, no effects were found of a dual task (fixed matrix tapping) loading spatial working memory.

Toms et al. (1993) studied conditional reasoning tasks and only found a performance impairment when the concurrent secondary task loaded the central executive, and not when the task loaded visuo-spatial working memory. This pattern of results was found both with visual (e.g., "if it is a circle, then it is green"; "it is a circle"; therefore?) and nonvisual (e.g., "if I drink vodka, then I eat pizza"; "I drink vodka"; therefore?) contents. Klauer et al. (1997) replicated the results of Toms et al. and found no spatial interference in conditional reasoning with similar contents (e.g., "if there is a circle, then there is a triangle", "there is a circle"; therefore?). However, they were able to induce visuo-spatial reasoning strategies by using a special training procedure which was aimed to reduce the impact of non-analytic heuristics (see also Meiser et al., 2001).

The findings of Vandierendonck and De Vooght (1997) and of Klauer et al. (1997) yield support for the mental model theory of reasoning (e.g., Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). According to this theory, reasoners go through three phases to infer a conclusion from a set of premises. In a first phase, they interpret the premises and construct an initial representation or mental model that represents these premises. Next, a conclusion is inferred from this initial model, and in the final phase, a search for counterexamples is performed by envisaging alternative conclusions. If necessary, reasoners adapt the initial model, after which the cycle of inference and search for counterexamples is restarted.

In the present context, the first phase postulated by the theory is the more important one because it requires a process of comprehension of the premises and of translation of this information into an initial model representing as much as possible the structural properties of the situation as described in the premises (see Johnson-Laird & Byrne, 1991). If the premises have a spatial content, it may be expected that the initial model represents this spatial structural information, whereas for premises with a nonspatial content, there is no need for such a structural representation. It is, therefore, fairly straightforward to assume visuo-spatial working memory (or VSSP, in Baddeley's terminology) involvement in problems with a spatial content. The findings reported by Klauer et al. (1997) and Vandierendonck and De Vooght (1997) actually support this interpretation.

The same logic could be extended to reasoning tasks that do not rely so heavily on spatial relations as the ones used by these authors. More specifically, in the case of conditional reasoning, it could be argued that Toms et al. (1993) did not find visuo-spatial interference because they used only problems that do not correspond to a spatially ordered reality or a spatial representation of it. If, on the contrary, the terms in the premises were to refer to spatially relevant orderings, then it may be easier for the reasoner to construct a spatial analogue and then to check whether later information is consistent with the spatial model. If this hypothesis is correct, then conditional reasoning could also be impaired by a concurrent spatial task, on condition that the reasoning contents trigger a spatial representation (see also Gattis & Dupeyrat, 2000). Note, however, that such an effect of problem content cannot be reconciled with the other main theory of reasoning, the logical competence theory (Braine, 1978; Braine & O'Brien, 1991; Braine, Reiser, & Rumain, 1984; Rips, 1983, 1994). According to this theory, reasoning is rule-based; therefore there is no need to assume that content (spatial vs nonspatial) of a premise or a term matters to the reasoning process. This issue will be discussed in more detail later.

It was the purpose of the present work to test the predictions sketched above. To that end, reasoners solved conditional reasoning problems with spatial and with nonspatial content under single-task conditions or concurrently with a tapping task loading visuo-spatial working memory. We predicted a performance impairment only when the reasoning problems had spatial contents and were solved concurrently with a spatial tapping task. The rationale for this prediction is that the VSSP is loaded by the reasoning task with spatial contents as well as by the spatial tapping, which results in a suboptimal allocation of resources to these tasks, and also in triggering selective interference. From a mental models perspective, it is mainly in the initial phase of problem solving, namely during model construction, that this effect would operate. The processing of the second premise is not expected to be slowed down because, in conditional reasoning, the second premise does not contain additional information that must be included in the model. Hence, it was expected that processing of the first premise in particular, would be delayed under the conditions of a concurrent load on spatial problems.

METHOD

Participants and design

A total of 42 first-year students enrolled at the Faculty of Psychology and Educational Sciences at the University of Gent participated for course requirements and credit. They were randomly assigned to the eight cells resulting from a 2 (Content: Nonspatial versus spatial relational content), × 2 (Counter-balancing over memory load conditions) × 2 (Working memory load: No load vs spatial load) factorial design. Only working memory load was manipulated within-subjects.

Materials

Four types of conditional problems were used, of which two were always valid and two were not, respectively modus ponens (MP: given $p \rightarrow q$ and p the conclusion q is valid), modus tollens (MT: given $p \rightarrow q$ and q, the conclusion $\neg p$ is valid), denial of the antecedent (DA: given $p \rightarrow q$ and $\neg p$, the conclusion $\neg q$ is not valid), and affirmation of the consequent (AC: given $p \rightarrow q$ and q, the conclusion p is also not valid). By introducing negations in the terms of the first premise of these conditional problems, four different variants of the first premise are obtained: $p \rightarrow q$, $p \rightarrow \neg q$, $\neg p \rightarrow q$, and $\neg \mathrm{p} \rightarrow \neg q$. Concomitantly, within each problem type, the second premise and the conclusion were varied; if, for example, the first term is $\neg p$, an MP problem requires that the second premise is $\neg p$, whereas a DA problem would have p as second premise. Given four problem types and four levels of negation in the first premise, there are sixteen different problem types to be considered.

These 16 problem types were realised with two different contents. One set of problems used spatial relations as in the following example:

If Pete lives to the right of Paul then Stan does not live to the right of Kurt
Pete lives to the right of Paul
Conclusion: Stan does not live to the right of Kurt
Correct answer: valid

The corresponding problem in the nonspatial set was then:

If Pete plays tennis with Paul then Stan does not play tennis with Kurt
Pete plays tennis with Paul
Conclusion: Stan does not plays tennis with Kurt
Correct answer: valid

All problems in both sets were completely matched on the names, but differed in the relations. Within each set the relations were varied, but in the spatial set, the relation was always a spatial one, such as “right of”, “left of”, “on top of”, “next to”, etc., while in the nonspatial set relations such as “plays tennis with”, “likes”, “laughs at”, … were used.

For each problem type of both (nonspatial and spatial) sets, two analogous items were constructed (the complete list of items is displayed in Appendix A). Each of these items was randomly assigned to one of the two working memory conditions. This procedure was carried out separately for each participant, such that these items were counterbalanced over working memory conditions. Hence, for each of the 16 problem types, all participants had to solve one item in the control condition and one in the working memory load condition, resulting in a total of 32 problems per participant.

Procedure

Participants were tested individually in small groups. The entire procedure was computer monitored. Instructions with a detailed example and problems were presented on a Pentium PC. Participants were instructed to respond “valid” when the conclusion necessarily followed from the two premises (this was the case for MP and MT problems, see the Materials section) and to respond “nonvalid” otherwise. The instructions did not mention the exact nature of the materials (nonspatial or spatial), but they only clarified the nature of the task; moreover, they were neutral with respect to methods or strategies that could be used.

After presentation of the instructions, the participants could ask for clarification and the experimenter paraphrased the written instructions. Once the instructions were clearly understood by the participants, the experiment started. It consisted of two blocks of problems, namely a single-task control block and a block in which participants solved the reasoning problems while concurrently performing a matrix-tapping task. Each block started with a practice problem, in which feedback was given on the correctness of the answer; on the other problems, no feedback was given. Within the two blocks, problems were presented in a different random order for each participant.

In the single-task condition, problems were presented with an inter-problem interval of 2 s. The problem started with a presentation of the first premise centred on the screen. Participants were instructed to take all the time they needed for reading and understanding this premise and to press simultaneously both buttons of the mouse to start the presentation of the next premise. The second premise was also presented self-paced in the centre of the screen. After clicking the two mouse buttons, a proposed solution was shown in the centre of the screen, and the participants were to press one mouse button if they thought the conclusion was valid and to press the other mouse button otherwise. The mapping of the answer (valid, nonvalid) to the mouse buttons (left, right) was randomly determined for each participant to counterbalance for stimulus–response compatibility effects. After 2 seconds the next problem started. Although all three phases in each problem were self-paced, a maximum time of 90 s was allowed for each premise and of 60 s for the conclusion. In order to avoid confusion by unintentional double button clicks, a time lock of 250 ms was imposed after each single click during which button clicks were not effective. Response times as well as responses were registered for the subsequent data analysis.

Problem presentation followed the same general scheme in the dual-task condition, but adapted for a concurrent execution of the secondary task. Like Toms et al. (1993) and Vandierendonck and De Vooght (1997), a matrix-tapping task was used to load visuo-spatial working memory. Each problem started with a presentation of the sequence of keys to be used in the tapping task. To that end a 3 × 3 matrix of unlabelled squares representing the numeric keypad was shown on the screen and the keys to be tapped were sequentially highlighted. This pattern was shown twice. Next a signal was presented to start the key-tapping sequence, which was to be performed with the index finger of the right hand on the unlabelled (i.e. the numbers were covered) numeric pad of the keyboard. After 5 s the presentation of the reasoning problem started and ran off in completely the same way as in the single-task condition. Tapping continued until the problem was answered and a stop signal was presented. In order to avoid direct motor interference the secondary task was always performed with the right hand, while the answers to the reasoning problem, as well in the single-task as in the concurrent task condition, were given by operating the mouse with the left hand.

RESULTS

Separate analyses were conducted for premise and solution processing time and accuracy. The basic design for these analyses was based on repeated measurements. In agreement with the suggestions formulated by McCall and Appelbaum

(1973) for a correct analysis of repeated measures data, multivariate analyses were performed with the values in the cells of the within-subject part of the design as the dependent variables. Hypotheses were tested by means of contrasts in the independent and the dependent variables.

Processing time

The basic design for the analysis of the processing times was a 2 (Content: Nonspatial versus spatial problems) × 2 (Counterbalancing) × 2 (Working memory load: Single-task versus dual-task) × 4 (Problem types: Modus Ponens [MP], Denial of the Antecedent [DA], Affirmation of the Consequent [AC], and Modus Tollens [MT]) × 4 (Negation Type: no negations [+ +], negation of the consequent term [+ –], negation of the antecedent term [– +], and both terms negated [– –] × 3 (Problem phases: first premise, second premise, and solution) factorial design with repeated measures on the last four variables. Since the effect of the counterbalancing variable was not significant and did not interact with any of the other factors in the design, no further mention will be made of this variable. Table 1 displays the average processing times as a function of content, working memory load and problem phases.

There were no main effects of content or dual task, $F(1, 38) = 1.51$, $p > .22$ and $F < 1$, respectively, but processing time was longer for the first premise than for the second one or for the solution, $F(2, 37) = 93.25$, $p < .01$. Although the processing time of the first premise was not significantly longer under dual-task (M = 16.45 s) than under single-task (M = 15.06 s) conditions, $F(1, 38) = 2.22$, $p > .14$, the effect of working memory load on the first premise interacted with content, $F(1, 38) = 5.39$, $p < .03$, as predicted. This is shown in the first row of Table 1. The working memory load slowed down processing time of the first premise when the content was spatial, $F(1, 38) = 7.27$, $p < .01$, but not when the content was not spatial, $F < 1$. Interestingly, the interaction of content and working memory load is only present for the processing of the first premise. Time used to process the second premise and to produce the solution do not seem to be affected, respectively $F(1, 38) = 1.39$, $p > .24$ and $F < 1$.

TABLE 1
Average processing time (seconds) in each of the three problem phases as a function of problem content and working memory load

	Nonspatial problems		*Spatial problems*	
	Single-task	*Dual-task*	*Single-task*	*Dual-task*
Premise 1	14.50	13.72	15.61	19.19
Premise 2	5.26	4.40	4.54	4.60
Solution	4.19	3.99	3.89	4.39

Moreover, the interaction effect of content and working memory load on the processing of the first premise interacted with negation type, $F(3, 33) = 3.74$, $p < .02$. As can be seen in Table 2, the interaction effect was much greater for problems with negations in the antecedent and/or the consequent term than for problems without negations, $F(1, 38) = 8.80$, $p < .01$. In contrast, the interaction effect of content, working memory load and problem type was not significant, $F < 1$.

Accuracy

Solution accuracy was analysed by means of a 2 (Content) × 2 (Counterbalancing) × 2 (Working memory load) × 4 (Problem types: Modus Ponens [MP], Denial of the Antecedent [DA], Affirmation of the Consequent [AC], and Modus Tollens [MT]). The dependent variable was the number of correctly solved problems in each problem category (maximum four). Again, the counterbalancing factor had no effect and did not interact with the other factors in the design.

As can be seen in the upper panel of Table 3, there were no overall effects of content or visuo-spatial memory load, respectively $F(1, 38) = 1.21$, $p > .27$ and $p < 1$, but the effect of problem categories was significant, $F(3, 36) = 107.77$, $p < .001$. For none of the problem categories, was the contrast between the single-task and the dual-task condition significant. When the factor of content was combined with this contrast, no significant differences were found.

A similar analysis was performed on the accuracy per problem type where the types were defined on the -basis of the occurrence of negations in the premises. The lower panel of Table 3 displays the averages in each of the four negation type categories ([+ +], [+ –], [– +], [– –]). Again, for none of the four problem types, was the contrast between the single- and the dual-task condition reliable. However, when combined with content, the contrast on the most difficult problem, the one with two negations, was significant, $F(1, 38) = 4.72$, $p < .05$. The working memory load affected accuracy for spatial items with two

TABLE 2
Average processing time (seconds) as a function of problem content, working memory load, and negation type

	Nonspatial problems		*Spatial problems*	
	Single-task	*Dual-task*	*Single-task*	*Dual-task*
+ +	14.09	14.56	17.83	19.04
+ –	15.77	13.88	14.40	19.95
– +	15.11	14.61	16.59	21.77
– –	13.04	11.84	13.63	15.98

TABLE 3
Average number of correctly solved problems per problem category as a function of problem content and working memory load

	Nonspatial problems		*Spatial problems*	
	Single-task	*Dual-task*	*Single-task*	*Dual-task*
MP	3.61	3.61	3.58	3.56
DA	1.18	1.05	1.72	1.76
AC	1.47	1.18	1.52	1.59
MT	2.20	2.65	2.20	2.15
+ +	2.19	2.05	2.00	2.24
+ –	2.07	2.05	2.57	2.99
– +	2.06	2.00	2.20	2.05
– –	2.14	2.37	2.25	1.72

negations, but not for nonspatial items, respectively $F(1, 38) = 4.56$, $p < .05$ and $F < 1$.

Secondary task performance

To rule out the possibility that the interaction effect of working memory load and content is due to worse secondary task performance in the nonspatial condition, we tested whether tapping performance (*TP*, for the formula used, see Appendix B) differed between the two content conditions. This is not the case: Tapping performance was even slightly better in the nonspatial condition ($M = 69.7$) than in the spatial condition ($M = 67.3$), but this difference was not significant, $F < 1$.

DISCUSSION

These results are very clear. On one count they confirm the results reported by Toms et al. (1993): with nonspatial problem content, a concurrent task loading visuo-spatial working memory task does not interfere with reasoning in conditional reasoning problems. However, the present results propose an important qualification to this conclusion. When the premises in the reasoning problems are based on spatial propositions, the first premise is processed about 3.5 s slower in the dual-task than in the single-task condition. This suggests that the internal model that is built to represent the information in the problem is of a spatial nature. Moreover, this selective effect of working memory load is more pronounced in problems with negations in either the antecedent term, the consequent term, or both. This is probably due to the fact that building a spatial representation of the information in the first premise requires one or more extra working memory manipulations when some of the information is negated (e.g., converting a "not left" representation into a more economical "right" relation). Similarly, although performance accuracy is not generally affected, performance for problems with negations in both the antecedent and the consequent term is slightly impaired under the combination of a concurrent visuo-spatial task and a spatial content. The interpretation of these interaction effects in terms of an increased number of working memory manipulations due to negations, rather than in terms of problem difficulty as a function of logical structure of the problem (i.e., MP, DA, AC, or MT), is compatible with the observation that the dual-task interference effects did not interact with problem type, although performance for DA and AC problems was significantly worse than for MP and MT problems.

It is interesting to note that apart from the small effect on solution accuracy of problems with two negations, essentially the processing time needed for the first premise is affected. This suggests that the effect of the combination of dual task and content operates early in processing. The complete absence of an effect while processing the second premise and during the solution phase indicates that once the first premise has been properly understood and represented, no further difficulties are to be expected for the reasoner.

One may wonder why Toms et al. (1993) did not find a similar effect. After all, they not only used nonvisual (e.g., "if I drink vodka, then I eat pizza"; "I drink vodka"; therefore?), but also visual problem contents (e.g., "if it is a circle, then it is green"; "it is a circle"; therefore?). First, it is possible that neither of these problems, not even the visual ones, triggered a spatial representation. This is in accordance with recent work of Knauff and Johnson-Laird (2002) who showed that ease of visualisation and the degree to which problem contents can be mapped onto a spatial representation have dissociable effects on reasoning performance. In this view, it could be interesting to investigate involvement of visual working memory in conditional reasoning with similar (visual) contents as that used by Toms et al., using a dual task that only loads the imagery component, and not the spatial subsystem, of the VSSP. Second, as Toms et al. did not study premise reading time, it was not so easy to detect the effect, especially as the present results indicate that early processing is especially important.

In view of our results, it may also be interesting to further investigate the nature of the spatial mental representation by exploring the effect of different kinds of spatial relations (i.e., symmetric vs asymmetric, "left–right" vs "on top of", …) on working memory involvement. An illustrative regression analysis of our data suggests that our findings may be generalised across different kinds of spatial relations, since processing times of the first premise were not related to symmetry status of the relation ($p > .80$), whereas spatial nature was ($p < .05$). But of course, this experiment was not designed to find these effects, so that future research is necessary to produce more convincing evidence concerning this issue.

The present set of findings is neatly consistent with the mental models framework proposed by Johnson-Laird (1983). This study reports a combined effect of spatial content and a concurrent visuo-spatial task on the processing of the first premise. As the premises are given in plain language, there is no reason whatsoever to assume that visuo-spatial working memory would be involved in conditional reasoning. However, the present results indicate that when the relational content is spatial, visuo-spatial working memory may be involved for the construction of a model of the premise. This corresponds to the first phase in the mental model inference cycle. The finding that this effect only occurs with a spatial content suggests that visuo-spatial working memory resources are engaged automatically if the content calls for a visuo-spatial representation. Moreover, this seems to be the case for both syllogistic and conditional reasoning: Spatial interference effects have been reported in syllogistic reasoning studies using spatial contents (e.g., Klauer et al., 1997; Vandierendonck & De Vooght, 1997), but not in studies using nonspatial contents (Gilhooly et al., 1993; Gilhooly et al., 1999). Similarly, Toms et al. (1993) found no effects of dual-tasks loading spatial working memory in conditional reasoning with nonspatial contents, contrary to the effects reported in the present study with spatial contents. It is also important to note that the spatial interference effects on reasoning with temporal contents reported by Vandierendonck et al. (1997) strongly suggest that the content does not need to be strictly spatial for these effects to emerge; instead, it suffices that the structural relationships can be easily mapped onto a spatial representation (e.g., a line with abstract tokens on it). Our results are also compatible with Barrouillet and Lecas (1999, 2002) who showed that the construction of mental models in conditional reasoning is influenced by working memory capacity, and by the semantic structure of the concepts that the conditional statement involves.

Although the present data show that encoding of the premise is very important, the finding does not seem to be consistent with a variant of the mental model theory, namely the verbal reasoning theory of Polk and Newell (1995). According to this theory, mental models are constructed (encoded) and modified (re-encoded) on the basis of the information presented in the premises. Since reasoning performance seems to be different for spatial than for nonspatial contents, the findings indicate that the medium used for representing the model(s) plays an important role even in a rather "simple" task like conditional reasoning.

In the same vein, it is difficult to see how these findings can be taken to support the other main reasoning theory, the logical competence theory (Braine, 1978; Braine & O'Brien, 1991; Braine et al., 1984; Rips, 1983, 1994). According to this theory, reasoning is rule-based and differences in difficulty between Modus Ponens and Modus Tollens problems are explained by assuming that the mind contains a rule for the former but not for the latter. Given that reasoning is supposed to operate by means of rules, there is no need to assume that spatial versus nonspatial content of a premise or a term matters to the reasoning process. Moreover, if the theory were extended for content-specificity, it would be a factor that matters before and after reasoning. This means that for some contents or contexts a translation could be required to represent the information in a format on which the mental rules can operate. Whether and why this could be necessary when the terms express spatial rather than nonspatial relations is not at all clear.

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APPENDIX A

English translation of the original (Dutch) stimuli

Problem type	*Negation type*	*Problem number*		*Nonspatial content**
		1	*Premise 1*	IF the prince is friends with the jester, THEN the jester is angry at the doctor
			Premise 2	the prince is friends with the jester
	+ +		*Conclusion*	THEREFORE, the jester is angry at the doctor doctor
		2	*Premise 1*	IF the king is a friend of the jester, THEN the doctor is angry at the jester
			Premise 2	the king is a friend of the jester
			Conclusion	THEREFORE the doctor is angry at the jester
		3	*Premise 1*	IF Piet plays tennis with Paul, THEN Gino does not play tennis with Koen
			Premise 2	Piet plays tennis with Paul
	+ −		*Conclusion*	THEREFORE Gino does not play tennis with Koen
		4	*Premise 1*	IF Alfred plays tennis with Sofie, THEN Antoine does *not* play tennis with Yves
			Premise 2	Alfred plays tennis with Sofie
			Conclusion	THEREFORE, Antoine does *not* play tennis with Yves
		5	*Premise 1*	IF the harp is *not* angry at the guitar, THEN the banjo is angry at the flute
			Premise 2	the harp is *not* angry at the guitar
	− +		*Conclusion*	THEREFORE, the banjo is angry at the flute
		6	*Premise 1*	IF the piano is *not* angry at the harp, THEN the harp is angry at the trumpet
MP			*Premise 2*	the piano is *not* angry at the harp
(valid)			*Conclusion*	THEREFORE the harp is angry at the trumpet

(continued overleaf)

Problem type	*Negation type*	*Problem number*		*Nonspatial content**
	– –	7	*Premise 1*	IF the horseman does *not* love his horse, THEN he does *not* love vegetarians
			Premise 2	the horseman does *not* love his horse
			Conclusion	THEREFORE, he does *not* love vegetarians
		8	*Premise 1*	IF the man does *not* love his table, THEN his monkey does *not* love him
			Premise 2	the man does *not* love his table
			Conclusion	THEREFORE, his monkey does not love him
DA (invalid)	+ +	9	*Premise 1*	IF Piet laughs at Konstantijn, THEN Koen laughs at Ronny
			Premise 2	Piet does *not* laugh at Konstantijn
			Conclusion	THEREFORE, Koen does *not* laugh at Ronny
		10	*Premise 1*	IF Hadewijch laughs at Sofie, THEN Sofie laughs at Johnny
			Premise 2	Hadewijch does *not* laugh at Sofie
			Conclusion	THEREFORE, Sofie does *not* laugh at Johnny
	+ –	11	*Premise 1*	IF the pigeon coos with Brecht, THEN it does *not* rain
			Premise 2	the pigeon does *not* coo with Brecht
			Conclusion	THEREFORE, it rains
		12	*Premise 1*	IF the sparrow sings with Emmanuel, THEN it does *not* snow
			Premise 2	the sparrow does *not* sing with Emmanuel
			Conclusion	THEREFORE, it snows
	– +	13	*Premise 1*	IF the cupboard does *not* look at the bath, THEN the cupboard looks at the toilet
			Premise 2	the cupboard looks at the bath
			Conclusion	THEREFORE, the cupboard does *not* look at the toilet
		14	*Premise 1*	IF the chair does *not* watch TV, THEN the chair looks at the poster
			Premise 2	the chair watches TV
			Conclusion	THEREFORE the chair does *not* look at the poster
	– –	15	*Premise 1*	IF the apple does *not* like the grape, THEN the grape does *not* like the pear
			Premise 2	the apple likes the grape
			Conclusion	THEREFORE the grape likes the pea

Problem type	*Negation type*	*Problem number*		*Nonspatial content**
		16	*Premise 1*	IF the kiwi does *not* like the peach, THEN the peach does *not* like the nut
			Premise 2	the kiwi likes the peach
			Conclusion	THEREFORE, the peach likes the nut
AC (invalid)	+ +	17	*Premise 1*	IF the coffee fits the milk, THEN the sugar fits the coffee
			Premise 2	the sugar fits the coffee
			Conclusion	THEREFORE, the coffee fits the milk
		18	*Premise 1*	IF the bread fits the chocolate spread, THEN the knife fits the bread
			Premise 2	the knife fits the bread
			Conclusion	THEREFORE, the bread fits the chocolate spread
	+ –	19	*Premise 1*	IF the red flag is like the yellow one, THEN the blue one is *not* like the yellow one
			Premise 2	the blue one is *not* like the yellow one
			Conclusion	THEREFORE, the red flag is like the yellow one
		20	*Premise 1*	IF the picture looks like the mirror, THEN the window does *not* look like the plant
			Premise 2	the window does *not* look like the plant
			Conclusion	THEREFORE, the picture looks like the mirror
	– +	21	*Premise 1*	IF the ball does *not* play with the stick, THEN the cap plays with the hat
			Premise 2	the cap plays with the hat
			Conclusion	THEREFORE, the ball does *not* play with the stick
		22	*Premise 1*	IF the sock does *not* play with the rack, THEN the sweater plays with the dress
			Premise 2	the sweater plays with the dress
			Conclusion	THEREFORE, the sock does *not* play with the rack
	– –	23	*Premise 1*	IF the troll does *not* marry the fairy, THEN the fairy does *not* marry the elf
			Premise 2	the fairy does *not* marry the elf
			Conclusion	THEREFORE, the troll does *not* marry the fairy
		24	*Premise 1*	IF the troll does *not* marry the fly, THEN the fly does *not* marry the dragon
			Premise 2	the fly does *not* marry the dragon
			Conclusion	THEREFORE, the troll does *not* marry the fly

(continued overleaf)

Problem type	*Negation type*	*Problem number*		*Nonspatial content**
MT (valid)	+ +	25	*Premise 1*	IF the red felt-tip teases the yellow one, THEN the green felt-tip teases the blue one
			Premise 2	the green felt-tip does *not* tease the blue one
			Conclusion	THEREFORE, the red felt-tip does *not* tease the yellow one
		26	*Premise 1*	IF the green egg teases the yellow one, THEN the white egg teases the black one
			Premise 2	the white egg does *not* tease the black one
			Conclusion	THEREFORE, the green egg does *not* tease the yellow one
	+ –	27	*Premise 1*	IF the tomato rots with the dough, THEN the cheese does *not* rot with the tomato
			Premise 2	the cheese rots with the tomato
			Conclusion	THEREFORE the tomato does *not* rot with the dough
		28	*Premise 1*	IF the cherry rots with the pie, THEN the chocolate does *not* rot with the cherry
			Premise 2	the chocolate rots with the cherry
			Conclusion	THEREFORE, the cherry does *not* rot with the pie
	– +	29	*Premise 1*	IF the cat is *not* afraid of the rat, THEN the dog is afraid of the rat
			Premise 2	the dog is *not* afraid of the rat
			Conclusion	THEREFORE, the cat is afraid of the rat
		30	*Premise 1*	IF the meat is *not* afraid of the pot, THEN the sauce is afraid of the pot
			Premise 2	the sauce is *not* afraid of the pot
			Conclusion	THEREFORE, the meat is afraid of the pot
	– –	31	*Premise 1*	IF 5 does *not* fight with 2, THEN 3 does *not* fight with 14
			Premise 2	3 fights with 14
			Conclusion	THEREFORE, 5 fights with 2
		32	*Premise 1*	IF 6 does *not* fight with 29, THEN 20 does *not* fight with 4
			Premise 2	20 fights with 4
			Conclusion	THEREFORE, 6 fights with 29

Problem type	*Negation type*	*Problem number*		*Spatial content**
MP (valid)	++	1	*Premise 1*	IF the prince is sitting to the left of the king, THEN the jester is sitting to the right of the doctor
			Premise 2	the prince is sitting to the left of the king
			Conclusion	THEREFORE, the jester is sitting to the right of the doctor
		2	*Premise 1*	IF the king is sitting to the left of the jester, THEN the doctor is sitting to the right of the jester
			Premise 2	the king is sitting to the left of the jester
			Conclusion	THEREFORE, the doctor is sitting to the right of the jester
	+ −	3	*Premise 1*	IF Piet is living to the right of Paul, THEN Gino does *not* live to the right of Koen
			Premise 2	Piet is living to the right of Paul
			Conclusion	THEREFORE, Gino does *not* live to the right of Koen
		4	*Premise 1*	IF Alfred is living to the right of Sofie, THEN Antoine does *not* live to the right of Yves
			Premise 2	Alfred is living to the right of Sofie
			Conclusion	THEREFORE, Antoine does *not* live to the right of Yves
	− +	5	*Premise 1*	IF the harp is *not* next to the guitar, THEN the banjo is lying next to the triangle
			Premise 2	the harp is *not* next to the guitar
			Conclusion	THEREFORE, the banjo is lying next to the triangle
		6	*Premise 1*	IF the piano is *not* to the left of the harp, THEN the harp is lying next to the trumpet
			Premise 2	the piano is *not* to the left of the harp
			Conclusion	THEREFORE, the harp is lying next to the trumpet
	− −	7	*Premise 1*	IF the horseman is *not* on his horse, THEN the dog is *not* sitting on his shoulders
			Premise 2	the horseman is *not* on his horse
			Conclusion	THEREFORE, the dog is *not* sitting on his shoulders

(continued overleaf)

Problem type	*Negation type*	*Problem number*	*Spatial content**	
		8	*Premise 1*	IF the man is *not* standing on the table, THEN the monkey is *not* standing on his shoulders
			Premise 2	the man is *not* standing on the table
			Conclusion	THEREFORE, the monkey is *not* standing on his shoulders
DA (invalid)	+ +	9	*Premise 1*	IF Piet is in front of Konstantijn, THEN Koen is in front of Ronny
			Premise 2	Piet is *not* in front of Konstantijn
			Conclusion	THEREFORE Koen is *not* in front of Ronny
		10	*Premise 1*	IF Hadewijch is in front of Sofie, THEN Sofie is in front of Johnny
			Premise 2	Hadewijch is *not* in front of Sofie
			Conclusion	THEREFORE Sofie is *not* in front of Johnny
	+ −	11	*Premise 1*	IF the pigeon is sitting on Brecht's head, THEN there is *not* a cloud above its head
			Premise 2	the pigeon is *not* sitting on Brecht's head
			Conclusion	THEREFORE, there is a cloud above its head
		12	*Premise 1*	IF the sparrow is sitting on Emmanuel's head, THEN there is *not* a bell above
			Premise 2	the sparrow is *not* sitting on Emmanuel's head
			Conclusion	THEREFORE, there is a bell above
	− +	13	*Premise 1*	IF the cupboard is *not* in front of the bath, THEN the cupboard is to the left of the toilet
			Premise 2	the cupboard is in front of the bath
			Conclusion	THEREFORE the cupboard is *not* to the left of the toilet
		14	*Premise 1*	IF the chair is *not* next to the TV, THEN the chair is to the right of the poster
			Premise 2	the chair is next to the TV
			Conclusion	THEREFORE the chair is *not* to the right of the poster
	− −	15	*Premise 1*	IF the apple is *not* next to the grape, THEN the grape is *not* next to the pear
			Premise 2	the apple is next to the grape
			Conclusion	THEREFORE the grape is next to the pear
		16	*Premise 1*	IF the kiwi is *not* next to the peach, THEN the peach is *not* next to the nut
			Premise 2	the kiwi is next to the peach
			Conclusion	THEREFORE, the peach is next to the nut

Problem type	*Negation type*	*Problem number*		*Spatial content**
AC (invalid)	+ +	17	*Premise 1*	IF the coffee is to the right of the milk, THEN the sugar is lying on top of the coffee
			Premise 2	the sugar is lying on top of the coffee
			Conclusion	THEREFORE the coffee is to the right of the milk
		18	*Premise 1*	IF the bread is to the left of the chocolate spread, THEN the knife is lying on top of the bread
			Premise 2	the knife is lying on top of the bread
			Conclusion	THEREFORE, the bread is to the left of the chocolate spread
	+ –	19	*Premise 1*	IF the red flag is under the yellow one, THEN the blue one is *not* above the yellow one
			Premise 2	the blue one is *not* above the yellow one
			Conclusion	THEREFORE, the red flag is under the yellow one
		20	*Premise 1*	IF the picture hangs under the mirror, THEN the window is *not* above the plant
			Premise 2	the window is *not* above the plant
			Conclusion	THEREFORE the picture hangs under the mirror
	– +	21	*Premise 1*	IF the ball is *not* to the right of the stick, THEN the cap is to the left of the hat
			Premise 2	the cap is to the left of the hat
			Conclusion	THEREFORE, the ball is *not* to the right of the stick
		22	*Premise 1*	IF the sock is *not* to the left of the rack, THEN the sweater is to the left of the dress
			Premise 2	the sweater is to the left of the dress
			Conclusion	THEREFORE, the sock is *not* to the left of the rack
	– –	23	*Premise 1*	IF the troll does *not* live under the fairy, THEN the fairy does *not* live above the elf
			Premise 2	the fairy does *not* live above the elf
			Conclusion	THEREFORE, the troll does *not* live under the fairy
		24	*Premise 1*	IF the troll does not live under the fly, THEN the fly does not live above the dragon
			Premise 2	the fly does not live above the dragon
			Conclusion	THEREFORE, the troll does not live under the fly

(continued overleaf)

Problem type	*Negation type*	*Problem number*		*Spatial content**
MT (valid)	+ +	25	*Premise 1*	IF the red felt-tip is on top of the yellow one, THEN the yellow one is to the right of the blue one
			Premise 2	the yellow one is *not* to the right of the blue one
			Conclusion	THEREFORE, the red felt-tip is *not* on top of the yellow one
		26	*Premise 1*	IF the red egg is to the left of the yellow one, THEN the white one is to the right of the black one
			Premise 2	the white one is *not* to the right of the black one
			Conclusion	THEREFORE, the red egg is *not* to the left of the yellow one
	+ –	27	*Premise 1*	IF the tomato is on top of the dough, THEN the cheese is *not* under the tomato
			Premise 2	the cheese is under the tomato
			Conclusion	THEREFORE, the tomato is *not* on top of the dough
		28	*Premise 1*	IF the cherry is on top of the pie, THEN the chocolate is *not* under the cherry
			Premise 2	the chocolate is under the cherry
			Conclusion	THEREFORE, the cherry is *not* on top of the pie
	– +	29	*Premise 1*	IF the cat is *not* to the left of the rat, THEN the dog is to the right of the rat
			Premise 2	the dog is *not* to the right of the rat
			Conclusion	THEREFORE, the cat is to the left of the rat
		30	*Premise 1*	IF the meat is *not* to the left of the pot, THEN the sauce is to the right of the pot
			Premise 2	the sauce is *not* to the right of the pot
			Conclusion	THEREFORE, the meat is to the left of the pot
	– –	31	*Premise 1*	IF 5 is *not* to the right of 2, THEN 3 is not to the left of 14
			Premise 2	3 is to the left of 14
			Conclusion	THEREFORE, 5 is to the right of 2
		32	*Premise 1*	IF 6 is *not* to the right of 29, THEN 20 is not to the left of 4
			Premise 2	20 is to the left of 4
			Conclusion	THEREFORE, 6 is to the right of 29

*Italics (e.g., *not*) and capitals (e.g., IF … THEN are printed here for reasons of clarity but were not used in the actual stimulus presentation

APPENDIX B

The following formula was used to calculate secondary task performance:

$$TP = \frac{nresp - ns - ni - nd}{nresp} \times 100$$

with:	TP	=	tapping performance	
	nresp	=	number of tapped keys	
	ns	=	number of skipped keys	(error that occurs when a key of the spatial sequence is skipped)
	ni	=	number of intrusions	(error that occurs when a key of the spatial sequence is tapped at the wrong moment)
	nd	=	number of doubles	(error that occurs when a key of the spatial sequence is tapped twice)