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Working memory components of the Corsi blocks task

André Vandierendonck[1]*, Eva Kemps[2], Maria Chiara Fastame[3] and Arnaud Szmalec[1]
[1]Ghent University, Belgium
[2]Flinders University, Australia
[3]University of Pavia, Italy
[4]Ghent University, Belgium

A computerized version of the Corsi blocks task (Milner, 1971) was assessed for standard forward-recall order (Experiments 1 and 3) and for reversed-recall order (Experiments 2 and 3) either in a single-task or in a dual-task design combined with articulatory suppression, matrix-tapping, random-interval generation or fixed-interval generation as concurrent tasks during the encoding stage. Concurrent performance of the matrix-tapping task impaired memory performance for short as well as for longer block sequences. The random-interval generation task, which loads executive processes, impaired memory performance mainly at intermediate- and longer-sequence lengths, while fixed-interval generation, which is presumed to put no load on executive processing, did not show any effect. Articulatory suppression did not impair memory performance on forward-recall order, but it impaired memory for longer sequences in the backward-recall condition in Experiment 2, but not in Experiment 3. The results are discussed within the context of the working-memory model of Baddeley and Hitch (1974).

The Corsi blocks task was developed in the early 1970s as a visuospatial counterpart to the verbal-memory span task (Milner, 1971). Over the years, it has frequently been used to assess visuospatial short-term memory performance in adults (e.g. Smyth & Scholey, 1992), children (e.g. Orsini, Schiappa, & Grossi, 1981), and patients with neuropsychological deficits (e.g. Vilkki & Holst, 1989). The original Corsi apparatus consisted of a set of nine identical blocks ($3 \times 3 \times 3$ cm) irregularly positioned on a wooden board (23×28 cm). The experimenter points to a series of blocks at a rate of one block per second. Subsequently, the participant is required to point to the same blocks in their

*Correspondence should be addressed to André Vandierendonck, Department of Experimental Psychology, Ghent University, Henri Dunantlaan 2, B-9000 Ghent, Belgium (e-mail: andre.vandierendonck@ugent.be).

order of presentation. The length of the block sequences increases until recall is no longer correct. Numerous variations have since been employed in both display characteristics (e.g. colour, number and size of the blocks, block placement, size of the board) and test administration (e.g. presentation rate, block sequences, recall order, scoring technique) (for a review, see Berch, Krikorian, & Huha, 1998). Despite its wide-ranging use, to date very little research has been conducted into the cognitive processing functions underlying performance on the Corsi blocks task. Previous research efforts were mainly concerned with establishing a double dissociation between verbal span and block span, in both healthy controls (Orsini *et al.*, 1986) and patients with selective brain damage (e.g. De Renzi & Nichelli, 1975; Hanley, Young, & Pearson, 1991).

The present study aimed to explore the information-processing operations measured by the Corsi blocks task within the working-memory framework developed by Baddeley and Hitch (1974; and see also Baddeley, 1986, 1990). Their multi-component model comprises a central executive and two slave systems, the phonological loop and the visuospatial sketch pad. The central executive serves as an attentional control system which is responsible for coordinating the operations of the subsidiary slaves. The phonological loop is responsible for the temporary storage and processing of verbal material. The visuospatial sketch pad performs a similar function for visuospatial material.

Symth and Scholey (1992) employed the Corsi blocks task in a selective interference paradigm to investigate the factors determining visuospatial immediate memory. Results revealed a dual-task disruption from a spatial secondary task, but not from a verbal task. The authors interpreted these findings as showing that immediate serial recall of a set of spatial targets taps the resources of the visuospatial sketch pad. However, owing to its sequential nature, the Corsi blocks task may not be a pure measure of visuospatial processing (Berch *et al.*, 1998).

If the Corsi blocks task were to rely solely on visuospatial working-memory resources, task performance would be expected to be impaired by concurrent irrelevant visuospatial material, but not by simultaneously presented material loading the phonological and attentional/executive working-memory subsystems. More specifically, in the light of the functional dissociation between verbal and visuospatial working-memory (e.g. Baddeley & Lieberman, 1980), it would be expected that verbal suppression does not disrupt block span, as has been shown by Smyth and Scholey (1992). Similarly, a central executive suppression task would not be expected to interfere with block recall. However, if performance on the Corsi blocks task were to involve other working-memory components, verbal and/or executive suppression might also be expected to interfere with recall.

It has been shown that verbal-memory span is impaired mainly by phonological suppression (e.g. Baddeley & Hitch, 1974). Executive suppression tasks have also been shown to disrupt verbal span. Executive interference techniques with a phonological component, such as backwards counting (e.g. Vallar & Baddeley, 1982) and random letter or digit generation (e.g. Baddeley, 1966; Salway & Logie, 1995), have a detrimental effect on verbal serial recall, whereas techniques without obvious phonological features, such as the random-time-interval generation task (Vandierendonck, De Vooght, & Van der Goten, 1998a) or the random-interval repetition task (Vandieredonck, De Vooght, & Van der Goten, 1998b) have an effect only on the recall of longer verbal sequences and at supra-span level, if at all. Interestingly, generating and repeating fixed time intervals (Vandierendonck *et al.*, 1998a, 1998b) does not affect either sub-span or supra-span performance. In the light of the postulated symmetry between the verbal and visuospatial working-memory subsystems (for a review, see Logie, 1995), a concurrent executive suppression task which does not put a significant load on either of the slave systems may thus be expected to interfere with Corsi span performance on longer block sequences or at the supra-span level.

These expectations were tested in three experiments using a dual-task methodology. The Corsi blocks task was combined with several concurrent suppression tasks, known to load the various working-memory systems. The secondary tasks included a verbal task, a visuospatial task and an attentional task. The verbal task consisted of articulatory suppression which requires participants to continuously repeat aloud the word 'the'. This task has been shown to disrupt the operation of the phonological loop. The visuospatial task comprised the continuous sequential tapping task, also known as the matrix-tapping task. This task requires participants to repeatedly tap four keys arranged in a square (Farmer, Berman, & Fletcher, 1986); it has been found to interfere with the functioning of the visuospatial sketch pad. The attentional interference task involved the random-interval generation task whereby participants have to tap a random temporal pattern (Vandierendonck *et al.*, 1998a). As noted above, generation of random time intervals has been shown to selectively disrupt the central executive. To control for potential effects of motor interference, a fixed-interval generation condition was included. The latter requires participants to tap regular time intervals.

Performance for both forward- and backward-recall order was assessed. Studies in the verbal domain have shown that forward-recall of digits is better than backward-recall (Gardner, 1981), because reversing the order of a verbal sequence requires that the input be transformed and thus makes additional demands on executive processing resources (Schofield & Ashman, 1986). To date, only a handful of studies have compared forward and backward-recall with visuospatial material, with inconclusive results. For example, in a developmental study, Isaacs and Vargha-Khadem (1989) found no differences between the two procedures for block span, whereas Helmstaedter, Kemper, and Elger (1996) reported a slightly higher forward than backward Corsi span in epilepsy patients.

A computerized version of the Corsi blocks task was employed. Such a procedure has already been used by several researchers in both clinical (e.g. Joyce & Robbins, 1991) and experimental laboratory studies (e.g. Jones, Farrand, Stuart, & Morris, 1995; Smyth & Scholey, 1992).

EXPERIMENT 1

The first experiment compared standard forward Corsi span performance in a single-task condition with performance in several dual-task situations, namely articulatory suppression, matrix-tapping, random-interval generation (Vandierendonck *et al.*, 1998a), and fixed-interval generation in a within-subject design where order of tasks was counterbalanced over participants. If there is a symmetry between the verbal and the visuospatial subsystems of working-memory, we may expect impaired memory spans in the matrix-tapping and the random-interval generation conditions, but not in the articulatory suppression and the fixed-interval generation conditions.

Method

Participants and design

Twenty-five first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for partial course requirements and credit. They volunteered for this particular experiment. Participants were randomly assigned to the five between-subjects conditions of a 5 (counterbalancing)×5 (task) factorial design with repeated-measures on the last factor. Counterbalancing was achieved by means of a randomized Latin square.

Materials and procedure

The Corsi blocks procedure was adapted for computerized presentation on a 15-inch touch screen. The nine blocks were white 30×30 mm squares placed at their relative standard positions on a blue background. Presentation of a sequence of blocks was also computer-monitored: Each block in turn was highlighted by changing its colour to black for 1 s, with an inter-block time of 0.5 s.

A standard trial started with a 1,000 Hz sound during 400 ms to announce the start of a presentation. Next, the sequence of blocks was highlighted, and the presentation ended with a warning sound of 500 Hz for 400 ms. Immediately after this sound, the participant repeated the sequence by touching the squares sequentially in the correct order. Each time a square was touched, it turned black for 200 ms. This way, feedback was provided as to the efficiency of the touching operation. At the end of the repetition, the participant was required to hit the escape key to indicate the end of the answer. After an inter-trial interval of 2 s, the next trial started.

The complete test condition consisted of four randomly selected block sequences at each of the sequence lengths 3 through 8, which corresponds to a total of 24 sequences. Five such conditions were presented, one condition with the Corsi task on its own, and four conditions in which, concurrently with the presentation of the sequences, a secondary task was performed. These secondary tasks were articulatory suppression (continuously repeating the word 'de', the Dutch equivalent of 'the', about two to three times per second), matrix-tapping (hitting the four corners of the numeric keypad in counterclockwise order at a pace of two to three keys per second), random-interval generation (hitting the zero key of the numeric keypad to form an unpredictable sequence of inter-tap intervals at an average of one key press every second), and fixed-interval generation (hitting the zero key of the numeric keypad to produce inter-tap intervals of about 1 s).

In the dual-task conditions, a trial started with three short tone bursts (400 ms each) at 2000 Hz to indicate that the secondary task had to be started. After 5 s of dual-task performance, the trial started in the same way as in the single-task control condition. During presentation of the blocks, the secondary task had to be continued until the sound signalling the end of presentation was heard, so that in the recall phase, no secondary task was performed.

The experiment started with an explanation of the Corsi task followed by two practice trials. Then, the five task conditions (single-task, articulatory suppression, matrix-tapping, random-interval generation and fixed-interval generation) followed in one of five random orders based on a randomized Latin square. Each condition started with instructions explaining the secondary task and how it was to be combined with the presentation of a Corsi trial. At the end, the participants were told how many sequences (percentage) they recalled correctly.

One to 3 weeks later, the participants were invited for a debriefing in which the purpose and the main results of the experiment were explained.

Results

Detailed recordings were made of stimulus presentations and responses. All analyses were performed by means of a repeated-measures design in the context of a multivariate design using the multivariate general linear hypothesis.[1]

Per participant and per condition, the memory span was defined as the maximal sequence length that resulted in correct recall 50% of the time. To that end, a sequence was considered to be correctly recalled when at least two of the four sequences of that length were reproduced correctly. Memory span was then operationalized as the shortest length at which correct recall failed minus 1.

The average spans per condition are displayed in the upper panel of Table 1. As evidenced in this table, the mean span length differed as a function of task condition, $F(4, 17) = 13.38$, $p < .001$. Comparison of each of the dual-task conditions with the single-task control condition revealed a significant interference effect of matrix-tapping, $F(1, 20) = 46.88$, $p < .001$ and of random-interval generation, $F(1, 20) = 5.65$, $p < .05$, but no significant impairment of span due to articulatory suppression, $F(1, 20) = 2.58$, $p > .10$ and to fixed-interval generation, $F < 1$.

Table 1. Means and standard deviations of span and proportion recalled in the correct serial position as a function of task conditions in Experiment 1

	C	AS	MT	RIG	FIG
Span					
M	5.96	5.68	4.72	5.48	6.08
SD	0.92	0.73	1.04	1.10	0.89
Correct in position					
M	0.85	0.83	0.74	0.81	0.86
SD	0.07	0.08	0.10	0.08	0.08

Note. The abbreviations C, AS, MT, RIG and FIG are shorthands for, respectively, the control, the articulatory suppression, the matrix tapping, the random-interval generation and the fixed-interval generation conditions.

Two components of scoring may contribute to the span measure, namely the proportion of correct elements in the output irrespective of serial position and the proportion of elements correctly positioned.[2] Although both measures were subjected to analysis, only the analyses based on the latter measure will be reported here, because

[1] *In this report, the same data-analytic technique is used for all analyses based on a repeated-measures design. F approximations to the likelihood-ratio statistic are presented; all reported F values are exact.*

[2] *Both these scores are based on proportions, which may raise problems with respect to the normality of the distribution of scores. To avoid these problems, analyses were run as well on arcsin-transformed proportions as on the raw data. In all three experiments reported here, the results were very similar, and it is not possible to draw different conclusions from the two sets of analyses. Because interpretation of the raw data is more transparent, only the analyses of the raw data are reported here.*

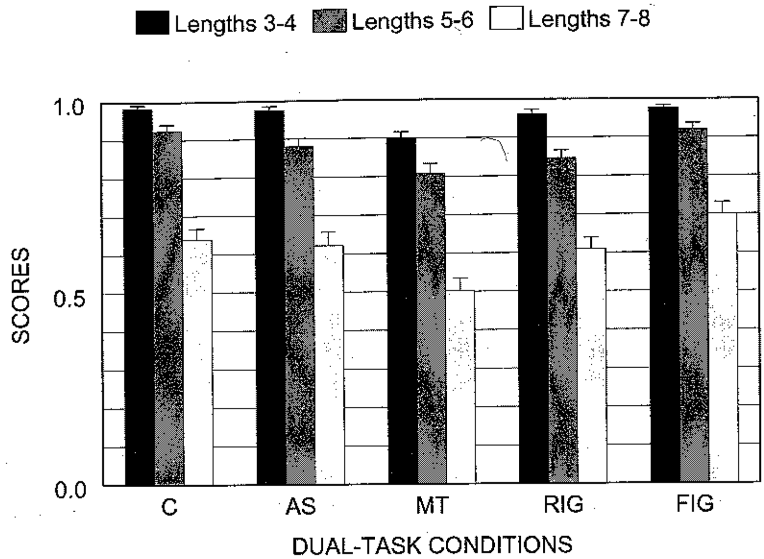

Figure 1. Proportion of correct recall in position (standard errors in the whiskers) as a function of task conditions and sequence length in Experiment 1.

it captures maintenance of the sequential order over the spatial array, whereas the analyses of the other measure by and large show the same effects.

The averages and standard deviations of the correctly recalled elements in correct position are displayed in the bottom panel of Table 1. The main effect of tasks was significant, $F(4, 17) = 15.31$, $p < .001$, and the contrasts of matrix-tapping and random-interval generation with the single-task control condition were the only significant ones: $F(1, 20) = 30.73$, $p < .001$ and $F(1, 20) = 8.27$, $p < .01$, respectively. In this analysis, we also tested the effect of the length of the sequence, by grouping lengths 3–4, 5–6 and 7–8. Its main effect was reliable, $F(2, 19) = 154.44$, $p < .001$, but the interaction of sequence length and task condition fell short of significance, $F(8, 13) = 2.47$, $p > .05$. The interference due to matrix-tapping was reliable at all three sequence lengths, $F(1, 20) = 17.28$, $F(1, 20) = 21.18$ and $F(1, 20) = 21.29$, all $p < .001$, whereas the interference due to the random-interval generation task was only reliable at the intermediate lengths, $F(1, 20) = 21.51$, $p < .001$. This pattern of findings can be inspected in Fig. 1.

Discussion

The main conclusion from this experiment is that the Corsi blocks task with a normal forward-recall order requires support from the visuospatial sketch pad but not from the phonological loop. When the sequence to be recalled becomes longer than three or four items so that the memory load increases, central executive resources are also called on. How the data support this conclusion is explained in the following paragraphs.

On the basis of the consideration that the Corsi blocks task requires short-term memorization of relative block positions in space in a temporal or sequential order, it was expected that performance would be impaired in conditions where encoding of the ordered spatial block positions competes with another visuospatial task requiring spatial processing for its execution, such as the matrix-tapping task. Under such conditions, the average span length was 1.2 positions shorter than in the control condition. Since the secondary task was not performed during reproduction, this finding must be attributed to the effect of the secondary task on encoding of the information. Viewed in the context of a multi-componential model of working-memory in which visuospatial storage forms an autonomous unit, it should also be expected that the effect of the secondary task would be present at all lengths, and this is exactly what was found in this experiment.

By and large, the effects of the random-interval generation task were also in line with the expectations. Indeed in the random-interval generation condition, span length was shortened by 0.5 positions. It was expected that the effects of the random-interval generation task would be rather small at the shorter lengths because the information load at shorter lengths does not exceed short-term visuospatial storage. As a consequence, executive intervention is hardly ever needed to maintain a good level of performance. At intermediate and long path lengths, on the contrary, the effects of random-interval generation should be larger. This was clearly confirmed for path lengths 5 and 6, but not for path lengths 7 and 8.

The fixed-interval generation task was included as a control for the random-interval generation task. If the effects of the random-interval generation task were caused by some form of general interference, then the fixed-interval generation task should exert the same effects as the random-interval generation task. If, on the contrary, the random-generation component is the important aspect of the random-interval generation task, there should be a neat difference between the effects of random-interval generation and fixed-interval generation. The latter interpretation was confirmed in this experiment, since the fixed-interval generation task did not affect any of the accuracy variables.

The articulatory suppression task was not expected to have an effect on Corsi blocks recall. This expectation was based on the assumption that the visuospatial and the phonological working-memory components are functionally separate subsystems (e.g. Baddeley & Lieberman, 1980), and even though the bias towards verbal recoding of visuospatial information is very strong, there is no evident way to attach verbal labels to the block positions used in the task. The expectation was borne out: Neither span length nor proportion recalled in correct serial order was affected by articulatory suppression.

Taken all together, it appears that performance on the Corsi blocks task involves both short-term visuospatial storage and executive control, the latter essentially at the intermediate path lengths. This finding is analogous to the observations reported by Vandierendonck *et al.* (1998a) with respect to verbal-memory span. They found that verbal short-term memory span was impaired by articulatory suppression and by the random-interval generation task at longer span lengths, while no effects of the fixed-interval generation task were detected. The strong parallelism between the two sets of findings suggests a functional similarity of the two slave systems and their relation to the central executive. Moreover, the findings indicate that the Corsi blocks test yields a measure of visuospatial short-term memory capacity in the same way that verbal span yields a measure of verbal-phonological short-term-memory capacity.

Converging evidence for the conclusion that the Corsi blocks task calls on visuospatial and executive resources may be obtained by studying backward-recall of the path presentations in the task. Upon presentation of a series of block positions, a representation of the path is constructed and maintained in visuospatial working-memory. If the sequence has to be reproduced in reversed order, executive control will be required to do this. Basically, there are two strategies to achieve reversed-recall. According to the first strategy, a reversed path is constructed during encoding: As the elements of the sequence come in, a reversed string is constructed, and this reversed string is maintained and rehearsed in working-memory. The second strategy stores the information in the order it has on input, and the maintained string is reversed at recall. Both strategies require executive control: The first strategy, which is predominantly used in verbal span tasks operates during encoding, the second strategy during recall. If it can be assumed that, in the Corsi blocks task, the reversal-at-encoding strategy is also the predominant one, it may be expected that in addition to visuospatial resources, the call on executive resources will be larger for the backward version of the task than for the forward version. Furthermore, if the load is too high, additional means may have to be recruited to perform the task efficiently.

These expectations were tested in Experiment 2, which was a replication of Experiment 1 with one change, namely that the paths had to be recalled strictly in the reversed order.

EXPERIMENT 2

Method

Participants and design

Twenty-five first-year students from the same source as in Experiment 1 participated for partial course requirements and credit. None of them participated in Experiment 1, but all volunteered for this particular experiment. Participants were randomly assigned to the five between-subjects conditions of a 5 (counterbalancing) × 5 (task) factorial design with repeated-measures on the last factor. Counterbalancing was achieved by means of a randomized Latin square.

Materials and procedure

The materials were the same as in Experiment 1, and the procedure was identical except for the requirement to recall the sequence of blocks strictly in the reversed order. Furthermore, instead of hitting the escape key at the end of recall, participants were required to hit the space bar. This change was made because the escape key was also used to end presentation of instructions at the start of a block. By using the space bar, the inadvertent skipping of instructions was avoided.

Results

Average reversed span scores and their standard deviations are displayed in the top panel of Table 2. The same effects seem to be present as in Experiment 1, even though, overall, the average span seems to be shorter. The effect of task condition was significant, $F(4, 17) = 11.30, p < .001$. Contrasts of the dual-task conditions to the control condition revealed significant impairment of performance due to articulatory suppression, $F(1, 20) = 5.04$, $p < .05$, matrix-tapping, $F(1, 20) = 22.92$, $p < .001$, and random-interval generation, $F(1, 20) = 6.35$, $p < .05$. Only fixed-interval generation did not impair performance, $F < 1$.

Average recall of blocks in correct position is displayed as a function of task condition in the bottom panel of Table 2. The main effects of task condition,

Table 2. Means and standard deviations of span and proportion recalled in the correct serial position as a function of task conditions in Experiment 2

	C	AS	MT	RIG	FIG
Span					
M	5.64	5.20	4.12	4.96	5.60
SD	1.13	1.06	1.18	1.31	1.13
Correct in position					
M	0.84	0.80	0.70	0.80	0.84
SD	0.021	0.017	0.022	0.020	0.015

Note. The abbreviations C, AS, MT, RIG and FIG are shorthands for, respectively, the control, the articulatory suppression, the matrix tapping, the random-interval generation and the fixed-interval generation conditions.

$F(4, 17) = 12.33$, $p < .001$ and sequence length, $F(2, 19) = 262.37$, $p < .001$, were significant. The overall interaction of these two variables fell short of significance, $F(8, 13) = 2.40$, $p > .07$. Dual-task versus single-task pair-wise contrasts were reliable for matrix-tapping, $F(1, 20) = 29.68$, $p < .001$, and for random-interval generation, $F(1, 20) = 5.58$, $p < .05$, and marginally significant for articulatory suppression, $F(1, 20) = 4.26$, $p > .05$. Again, fixed-interval generation did not affect performance, $F < 1$. As can be seen in Fig. 2, which displays the average recall in correct position as a function of task and sequence length, the dual-task effects varied with sequence length. Matrix tapping impaired performance at all sequence lengths: $F(1, 20) = 14.49$, $F(1, 20) = 25.69$, and $F(1, 20) = 13.35$ (all $p < .01$). The effect of random-interval generation was present at the longest sequences, $F(1, 20) = 5.42, p < .05$, as was the effect of articulatory suppression: $F(1, 20) = 13.35, p < .01$. Irrespective of the sequence length, finally, fixed-interval generation had no reliable effect on performance.

Discussion

In most respects, the results of Experiment 2 are similar to those obtained in Experiment 1. Moreover, they confirm the specific predictions formulated for the reversed-recall procedure: Reversed Corsi blocks performance was impaired by a concurrent visuospatial task and by a concurrent executive task. In addition, a concurrent articulatory suppression task resulted in poorer recall, especially at longer path lengths. Finally, as in Experiment 1, the fixed-interval generation task had no effect whatsoever on recall performance. Once more, this indicates that the effect of the random-interval generation task is not due to some kind of motor interference but is achieved from the efforts required to produce random-intervals.

These findings corroborate the view that the visuospatial paths are maintained in visuospatial short-term storage. If the paths become too long, the central executive is called for extra resources to support the maintenance of the visuospatial representation. However, with the instruction to recall the paths in reversed order, the degree of required control is larger. In order to cope with this more difficult situation, the participants may have called on verbal support, as can be inferred from the marginally

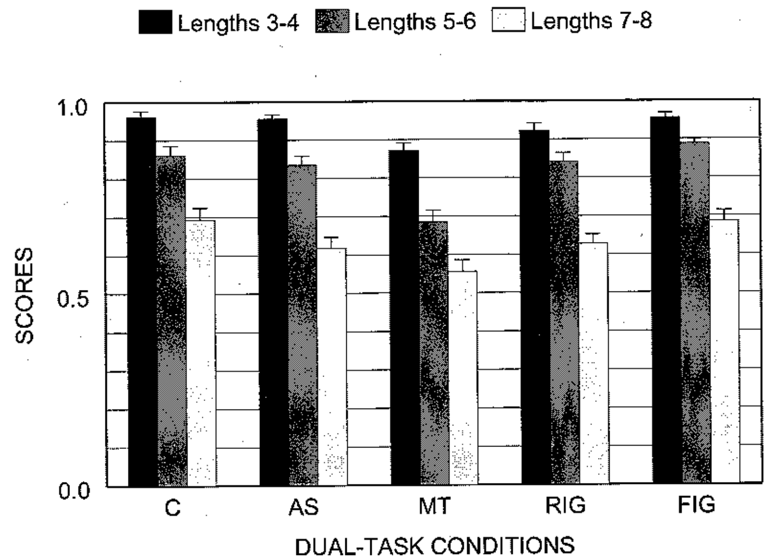

Figure 2. Proportion of correct recall per element as a function of task conditions and sequence length in Experiment 2.

significant articulatory suppression effect. It is not clear which form such a verbal support takes, but one could imagine that participants use area descriptions such as 'upper left', 'central', etc., which can help to monitor recall in a similar way as in self-instructions function in task switching (e.g. Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003). Especially with longer path lengths, this is a requirement to achieve an acceptable level of performance. This flexible management of the working-memory resources is disrupted again under concurrent articulatory suppression.

It could be argued that these findings go against the hypothesis corroborated in the first experiment, namely that the phonological loop and the visuospatial sketch pad are independent storage systems (cf. Logie, Zucco, & Baddeley, 1990). The present findings show that the two slave systems cooperate when this is required by the task conditions (see also Martein, Kemps, & Vandierendonck, 1999), but this does not imply that the stimulus representations can be simply interchanged between the two storage systems. On the contrary, the paths in the Corsi task are preferentially stored by means of visuospatial codes, and only when the capacity of this storage system is flooded are other possibilities called upon, namely recruitment of executive resources and, if the need arises, supportive verbal coding of the spatial information.

The motivation for running Experiment 2 was based on the hypothesis that in Corsi block backward-recall, just as in the verbal-span task, the sequence of block positions would be reversed during encoding. The results of Experiments 2 seem to be consistent with this hypothesis. The most critical prediction, though, requires a direct comparison of backward and forward-recall performance. This will be addressed in Experiment 3.

EXPERIMENT 3

Not much is known about the relative difficulty of forward and backward-recall in the Corsi blocks task (see Introduction and also Berch *et al.*, 1998). An analysis based on the combined data of Experiments 1 and 2 reveals a main accuracy difference between forward and backward span, $F(1, 48) = 4.59$, $p < .05$, which did not interact with task conditions, $F < 1$.

It could be argued, however, that such an analysis may be biased because the combined data come from two different experiments with two samples of participants that may differ in uncontrolled ways. In order to provide more stable data on the comparison of forward and backward visuospatial memory spans, a new experiment was designed in which the forward–backward contrast was a within-subject variable. In fact, like in Experiments 1 and 2, all manipulations were within-subject variations. Such a design also allows for the test of whether the two task conditions put a different load on the working-memory components.

An experiment in which forward and backward-recall are tested in a number of dual-task conditions requires an extensive testing session, however. To keep the duration of the testing session reasonable, it was decided to run two sessions, one with the forward test conditions and one with the backward test conditions. The order of the forward and backward session was counterbalanced.

Method

Participants and design

Thirty-six first-year students from the same source as in Experiments 1 and 2 participated for course requirements and partial credit. None of them had participated in either of the two previous experiments, but all volunteered for this particular experiment. They were randomly assigned to a 2 (session order) × 9 (condition order) between-subjects design. Both factors of this design were included merely for counterbalancing purposes. The first factor counterbalances the order of the forward and backward test sessions, while the second factor counterbalances the order of the conditions within the session. The nine test conditions included the five conditions that were also present in the previous experiments, namely control, articulatory suppression, matrix-tapping, random-interval generation and fixed-interval generation. In addition, four single-task control conditions were included for the four different secondary tasks. The nine orders were obtained by means of a randomized Latin square. Two different Latin squares were used for the two sessions. Each session started with two practice trials followed by a practice control condition with forward-recall in the forward-recall session and backward-recall in the backward-recall session. A second control condition was part of the counterbalancing scheme, and only the data for the latter condition were included in the data analysis.

Materials and procedure

For the forward testing conditions, the materials and the procedure were the same as in Experiment 1, and for the backward conditions, the same materials and procedure as in Experiment 2 were employed. In all conditions, recall was ended by hitting the space bar. In the single task controls for the secondary tasks, participants were requested to perform the task alone for a duration matching on the durations of the corresponding dual-task trials. Instead of four trials per task length, only two such trials were included, one in the forward and one in the backward testing session. The data collected this way allow for the test of dual-task tradeoffs.

Results

Average span scores and their standard deviations are displayed in the top panel of Table 3. The main effect of dual-task condition was significant, $F(4,31)=21.06, p<.001$, but the effect of recall condition was not reliable, $F(1,34)=2.75, p>.10$, and did not interact with dual-task condition, $F<1$. Contrasts of the dual-task conditions to the control condition revealed significant contrasts of matrix-tapping and random-interval generation, $F(1,34)=50.71, p<.001$ and $F(1,34)=9.41, p<.01$, respectively. The contrasts of articulatory suppression and fixed-time-interval generation were not statistically reliable, both $F<1$. Neither of these contrasts interacted with forward versus backward-recall. Although session order did not affect performance, $F<1$, it interacted with the effect of recall direction, $F(1,34)=13.17, p<.001$. Tested in one order, the difference between forward (5.39) and backward-recall (5.60) was smaller than when tested in the other order (respectively, 5.71 and 5.14). This essentially corresponds to an effect of practice: Both forward and backward-recall spans were shorter in the first test session (respectively, 5.39 and 5.14) than in the second test session (respectively, 5.71 and 5.60).

Table 3. Means and standard deviations of span and proportion recalled in the correct serial position as a function of task conditions in Experiment 3

	C	AS	MT	RIG	FIG
Span					
Forward					
M	5.86	5.89	4.64	5.44	5.92
SD	1.08	1.05	1.03	0.96	0.95
Backward					
M	5.61	5.75	4.56	5.14	5.81
SD	1.06	1.11	0.98	1.11	1.08
Correct in position					
Forward					
M	0.85	0.86	0.73	0.80	0.86
SD	0.09	0.08	0.11	0.09	0.07
Backward					
M	0.85	0.85	0.77	0.82	0.87
SD	0.09	0.08	0.10	0.09	0.07

Note. The abbreviations C, AS, MT, RIG and FIG are shorthands for, respectively, the control, the articulatory suppression, the matrix tapping, the random-interval generation and the fixed-interval generation conditions.

The bottom panel of Table 3 displays the proportion of blocks recalled in correct serial position as a function of the conditions. The main effects of dual-task and sequence length were significant, $F(4,31)=27.02, p<.001$ and $F(2,33)=261.55, p<.001$, respectively. Their interaction was also significant, $F(8,27)=5.15, p<.001$, as was the interaction of sequence length with forward/backward-recall direction, $F(2,33)=8.50, p<.001$. Again, recall direction interacted with session order, $F(1,34)=22.84, p<.001$, which again suggests a practice-based effect with better performance in the second session for both forward (0.83 versus 0.80) and backward-recall (0.86 versus 0.81). Contrasts of the dual-task conditions with the control condition revealed significant effects for matrix-tapping and random-interval generation, $F(1, 34) = 58.80, p < .001$ and $F(1, 34) = 10.71, p < .01$, respectively. The other contrasts failed to attain significance.

Further analysis of the interaction of dual-task and sequence length revealed reliable effects of matrix-tapping at all sequence lengths, $F(1, 34) = 7.60$, $F(1, 34) = 43.41$ and $F(1, 34) = 61.58$, all $p < .01$ for short, intermediate and long sequences, respectively. The effect of random-interval generation attained significance only for the long sequences, $F(1, 34) = 26.63$, $p < .001$. Figure 3 displays these scores as a function of dual-task conditions and sequence length (short: 3–4 blocks, intermediate: 5–6 blocks and long: 7–8 blocks) for the forward-recall condition, and Fig. 4 contains a similar display for the backward-recall condition. These figures also clearly indicate that the interaction of recall order with sequence length mentioned before is essentially due to a difference in recall level between forward and backward-recall at longer sequences, such that forward-recall seems to be *poorer* than backward-recall.

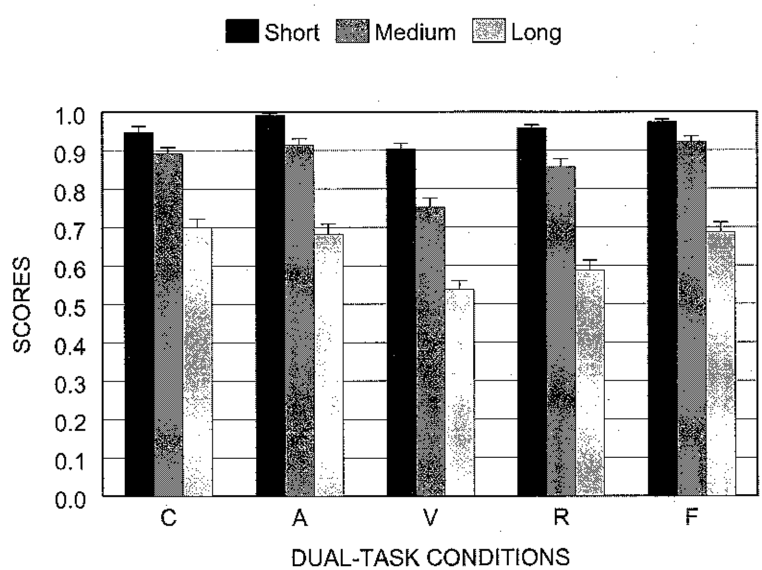

Figure 3. Proportion of correct recall in position as a function of task conditions and sequence length in the forward-recall conditions of Experiment 3.

In view of the recurrent finding of a practice effect, an analysis was conducted on the data from the single-task practice blocks which were not included in the data analysis as reported thus far. An analysis of the span data shows a neat and reliable difference between forward (5.55) and backward (5.33) span, $F(1, 34) = 4.80$, $p < .05$, and this difference is not contaminated by testing order since the order × recall direction interaction was not reliable, $F(1, 34) = 3.53$, $p > .05$.

An analysis of dual-task trade-off

When executing two tasks simultaneously, there are a number of ways for people to cope with this dual-task situation. Sometimes, it happens that performance on the

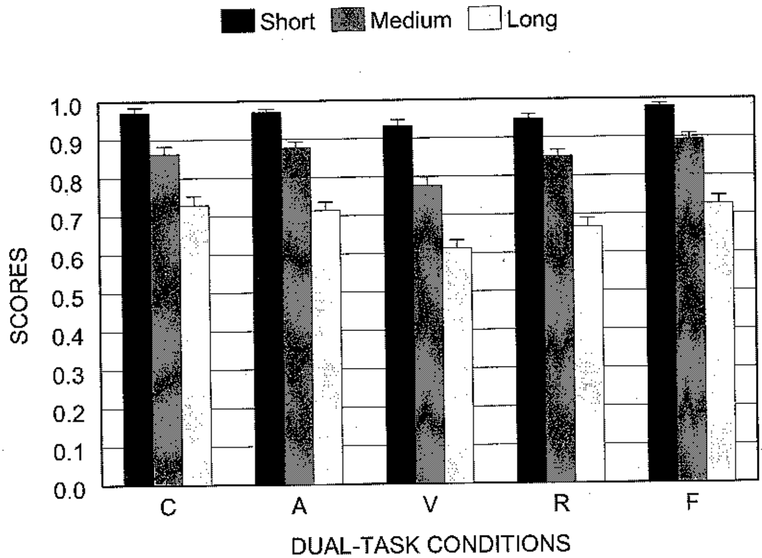

Figure 4. Proportion of correct recall in position as a function of task conditions and sequence length in the backward-recall conditions of Experiment 3.

primary task (here, the Corsi blocks task) is impaired to achieve a high level of performance on the secondary task, or vice versa. The results thus far show that span performance was impaired when the matrix-tapping or the random-interval generation task were generated simultaneously with the Corsi blocks task, while no impairment was observed with the fixed-interval generation task. In order to strengthen the conclusion obtained in the present study, an analysis is reported that compares performance on the secondary tasks performed under dual-task conditions and the secondary tasks performed alone.[3]

Performance on articulatory suppression, matrix-tapping, and random- and fixed-interval generation were analysed separately in a factorial design with task (single-task versus dual-task), recall direction (forward versus backward) and sequence length (in three levels) as independent variables where all were within-subject variables.

Articulatory suppression

The dependent variable was the number of words produced per second. Production was faster under single-task ($M = 2.48$) than under dual-task ($M = 1.95$) conditions, $F(1, 34) = 141.53$, $p < .001$. Overall, word production decreased as sequence length increased ($M = 2.38$, 219 and 2.08 in short, intermediate and long sequences, respectively), $F(2.33) = 39.71$, $p < .001$. The interaction of these two variables was also significant, $F(2, 33) = 34.16$, $p < .001$: The task effect was larger in shorter sequences (the mean difference dropped from 0.68 over 0.50 to 0.40). None of the other effects or interactions attained significance.

[3] *Control data were also collected for Experiments 1 and 2 on a separate group of participants. However, these data are not presented in the present report, because they are based on a between-subjects comparison, which is less compelling than the within-subject comparison, which is possible on the basis of Experiment 3. However, the results were completely similar.*

Matrix tapping

The proportion of correct key presses (correct key at correct position in the sequence) differed as a function of task-condition, $F(1,34)=7.73, p<.01$: Performance was better in single-task ($M=.805$) than in dual-task conditions ($M=.797$), but did not differ as a function of recall direction, $F(1,34)=2.98, p>.05$, or sequence length, $F(2,33)=2.09$, $p>.10$. The interaction of task and sequence length was reliable, $F(2,33)=7.55, p<.01$, indicating that the difference between the two task conditions increases with sequence length.

The time between key presses also varied as a function of task condition, $F(1,34)=21.28$, $p<.001$ and task duration, $F(2,33)=11.87$, $p<.001$, but these variables did not interact. Inter-tap times were longer in single-task ($M=661$ ms) than in dual-task conditions ($M=646$ ms) and decreased with the length of the sequence (from 681 to 632 ms).

Generation conditions

The random and fixed time sequences were analysed by means of a method described extensively elsewhere (Vandierendonck, 2000a, 2000b). For the present report, only an overall measure of the quality of tapping performance will be reported, namely the alternation index. This index has been shown to be sensitive to deviations from randomness in the direction of perseveration or alternation biases. It calculates the relative proportion of alternations in the sequence, so that high values (towards 1) indicate an alternation bias, whereas low values (below 0.5 and towards 0) indicate the presence of a perseveration bias.

The random and fixed sequences were entered into a single analysis so that a direct comparison of the qualities of both types of sequence would be possible. The other independent variables in the analysis were task (single versus dual) and recall direction (forward versus backward). Sequence length was not a separate variable because the data collected for the shortest sequences are less reliable. In general, sequences that did not contain a sufficient number of data points were not included in the analysis either. The alternation index was lower for random-interval generation (0.34) than for fixed-interval generation (0.49), $F(1,34)=44.51, p<.001$. Furthermore, the average value of the alternation index was higher for forward (0.43) than for backward (0.41) recall, $F(1,34)=4.84$, $p<.05$, but did not differ among single-task and dual-task (both 0.42) conditions, $F<1$. However, there was an interaction, $F(1,34)=5.95, p<.05$, such that for the random-interval generation task, the alternation index was larger in dual-task (0.35) than in single-task conditions (0.33), whereas the reverse pattern emerged for the fixed-interval generation task (respectively, 0.48 and 0.50).

Discussion

The main purpose of this experiment was to clarify whether backward-recall is more difficult than forward-recall in the Corsi blocks procedure. Although the forward and backward spans did not differ overall, the present data yield a number of indications that show that in some respects, backward-recall is more difficult than forward-recall, while in other respects, the reverse may hold. We first discuss the indications for better performance in forward-recall direction. A first indication comes from the practice effect that was clearly present in the span data. In the present experiment, the participants performed the Corsi blocks task 12 times spread over two sessions. This provides an important opportunity for practice and learning how to perform this kind of task. The findings clearly show that performance in the second session, which was held on average a week later, was much better than performance during the first session. More importantly, the gain seemed to be larger from forward to backward-recall than from backward to forward-recall. Moreover, an analysis on the practice blocks showed that without practice, the forward span was longer than the backward span.

This yields quite a strong indication that in normal circumstances, i.e. without extensive practice, forward span is longer than backward span in the Corsi blocks task. In some of the dependent variables used, however, backward-recall tended to be superior to forward-recall. This was especially the case with measures that rely strongly on the initial correct part of the recall, such as correct recall in position or the length of the initial correct segment (which was not reported here). It is clear that backward-recall has an advantage here. If it is assumed that visuospatial working-memory can hold about four spatially distinct and identifiable items (i.e. features bound together to form an object; Wheeler & Treisman, 2002), in longer sequences, these four items can be readily retrieved, while in forward-recall, the less recent items must be reproduced first. This may interfere with the recent elements in visuospatial storage. As this is obviously an important issue, we will come back to it in the General Discussion.

A second purpose of the present experiment was to check whether the dual-task effects would remain stable if the same participants were involved in both forward and backward-recall and whether, more specifically, there were any differences in working-memory load between forward and backward-recall. The strong and ubiquitous effect of matrix-tapping on recall performance was confirmed and seems to be similarly important in backward as in forward serial recall. The effect of random-interval generation was also clearly present in both recall conditions and had its strongest effect at longer sequence lengths. The effects of fixed-interval generation and articulatory suppression were not reliable.

The results of the trade-off analyses show that impaired performance on the primary memory task was not due to a better-than-normal performance on the secondary tasks. In the articulatory suppression tasks, speed of production was slower under dual-task than under single-task conditions. To the extent that any recall impairment was observed due to articulatory suppression, this is not achieved by trading recall accuracy for articulatory speed. On the contrary, the small and sporadic interferences due to articulatory suppression in the present experiment were accompanied by a poorer articulatory performance in these dual-task conditions. Similarly, matrix-tapping was performed more accurately under single-task than under dual-task conditions. Yet, the task was executed slightly faster under dual-task than under single-task conditions, which could be taken as indicating a trade-off in favour of the tapping task. However, this difference is quite small and similar in size to the difference between short and long sequences where tapping was faster in longer sequences. Nevertheless, matrix-tapping impaired recall reliably at all sequence lengths.

The normal tendency to alternate between shorter and longer intervals (Vandierendonck, 2000a, 2000b) did not occur in this experiment. Instead, there was an overall tendency towards perseveration. This indicates that random performance overall was well controlled. As this tendency to perseverate was not as strong under dual-task conditions, the data suggest that performance was less controlled under dual-task conditions.

Table 4. Probability level of the null-hypothesis for all the dual-task effects on span length and proportion recalled in correct serial position in Experiments 1–3

	AS	MT	RIG	FIG
Experiment 1				
Span length	–	*	*	–
Proportion correct	–	*	*	–
Effect at length				
3–4	–	*	–	–
5–6	–	*	*	–
7–8	–	*	–	–
Experiment 2				
Span length	*	*	*	–
Proportion correct	*[a]	*	*	–
Effect at length				
3–4	–	*	–	–
5–6	–	*	–	–
7–8	–	*	*	–
Experiment 3				
Span length	–	*	*	–
Proportion correct	–	*	*	–
Effect at length				
3–4	–	*	–	–
5–6	–	*	–	–
7–8	–	*	*	–

Note. The abbreviations AS, MT, RIG and FIG are shorthands for, respectively, the articulatory suppression, the matrix tapping, the random-interval generation, and the fixed-interval generation conditions.
$*p < .05$.
[a] $p = .052$.

GENERAL DISCUSSION

It was the purpose of the present study to fill a gap in the research literature on the theoretical and practical utility of the Corsi blocks task. The frequent usage of the task notwithstanding, surprisingly little research has addressed the underlying cognitive processing mechanisms of the Corsi blocks task (Berch *et al.*, 1998). The present article focused more particularly on how the processing mechanisms described by the multi-componential working-memory model of Baddeley and Hitch (1974) are involved in the execution of the task.

The findings of the present study are summarized in Table 4. Per experiment and for each of the dual-task effects studied, the table shows the probability level of the effect (< 0.05 is considered to be statistically significant). In each of the three experiments, the effects of matrix-tapping and of random-interval generation were reliable both in their effect on span length and in their effect on the proportion of blocks recalled correctly in sequential order. The pattern of findings was also very consistent in that the effect of matrix tapping was always present at all sequence lengths, while the random-generation was present at intermediate (Experiment 1) or long sequences (Experiments 2 and 3). There was only one deviation from this overall picture, namely the finding of a significant effect of articulatory suppression in Experiment 2. It is not clear whether this is a coincidence. The finding was not replicated in Experiment 3, since there were no interaction of the effects with recall direction.

Taken together, these findings are clear and fit in well with the working-memory framework of Baddeley and Hitch (1974). In all three experiments, it was found that concurrent execution of the matrix-tapping task during stimulus presentation impairs performance of the immediately following recall, and this adverse effect on performance was reliable in sequences of all lengths both in backward and in forward-recall. Since it is well known that the matrix-tapping task calls on the visuospatial sketch pad (VSSP) for its execution, it may be concluded that the impaired recall is caused by interference of the two tasks. This conclusion is strengthened by the observation that matrix-tapping performance itself also suffered under dual-task conditions. The three experiments also showed that concurrent execution of the random-interval generation task during stimulus presentation impaired recall performance, and this effect tended to be stronger in longer sequences. In view of the evidence that this generation task calls on the central executive (e.g. Vandierendonck, 2000b) and that it suffered from the dual-task combination, it may be concluded that, especially for the longer sequences, extra resources are required to maintain the information by invoking the central executive.

The finding that the visuospatial input of the Corsi blocks task is represented preferentially with the help of the VSSP provides additional evidence in favour of the view that the two subsidiary working-memory systems, the VSSP and the phonological loop, operate relatively independently from each other. Especially the observation that articulatory suppression did not impair recall performance in the forward-recall conditions supports the conclusion that the phonological loop is not at all involved in normal (forward) Corsi blocks performance. With respect to the role of the phonological loop in backward-recall, the present data are less clear. In Experiment 2, a clear effect of articulatory suppression was observed in the longer sequences. However, this was not replicated in Experiment 3. Because it is unclear whether the effect observed in Experiment 2 is reliable, the present series of experiments cannot lead to a firm conclusion as to the possible involvement of the phonological loop in the backward Corsi task, and further experimentation would be welcome here.

As expected, there were also differences in performance elicited by the instruction to recall the paths in the forward or backward order. First, there was a quantitative difference. Spans were reliably longer in the forward than in the backward-recall condition, but this difference seemed to disappear or become smaller due to the extensive practice in Experiment 3. The finding of a difference between forward and backward-recall is consistent with the observation made by Helmstaedter *et al.* (1996) in epilepsy patients. We expected this result on the basis of considerations of central executive involvement: Because of the requirement to manipulate the incoming visuospatial information to obtain a reversed output, executive processes are engaged already in the encoding phase.[4] Interestingly, the same result was obtained in a verbal span task (Vandierendonck *et al.*, 1998a): Backward verbal spans were shorter than forward spans

[4] Reversing the path at recall is probably a useful strategy only with shorter paths. It is probably not easy to reverse paths that occupy the entire visuospatial storage and rehearsal capacity because some spare capacity is needed for this operation. The easiest solution seems to be to construct the reversed path immediately during input, and apparently this strategy is used in visuospatial as well as in verbal tasks.

and put a higher load on executive processes. This symmetry adds further evidence in favour of the view that the VSSP and the phonological loop are functionally similar (Logie, 1995).

A second difference between the forward and backward-recall tasks was qualitative. While, in both tasks, recall was disrupted by visuospatial and executive interference, at least in one of the experiments, the articulatory suppression task impaired backward-recall performance. Similar effects on forward-recall were not observed in the present study. This effect on backward-recall, if it is reliable, seems to indicate that phonological coding was a kind of last resort and was only called upon when the load became too high. Evidence for this interpretation can be found in the observation that articulatory suppression did not affect recall performance of paths with lengths in the range of 3–6.

Furthermore, it is interesting to note that the disruption of recall by articulatory suppression in the longer backward paths has no counterpart in the verbal domain. Vandierendonck *et al.* (1998a) observed no adverse effects of concurrent matrix-tapping on backward-recall of verbal spans. This may be taken as evidence contrary to the idea of a functional dissociation and equivalence between the VSSP and the phonological loop. We prefer a much simpler explanation, however. In view of the accumulating evidence in favour of such a functional equivalence (see, e.g. Kemps 1999, 2000; Logie, 1995), the observed asymmetry shows that the working-memory resources can be used flexibly if the need arises. Recoding of the visuospatial path information into a verbal format is probably not evident and is clearly not done in the forward-recall condition. In the backward-recall condition, however, the information load warrants the effort of supplementary coding. As a result, an impairment of performance is seen when articulation is concurrently suppressed. This does not speak against the dissociation view because, if it would, one should expect a similar effect in the forward-recall procedure, given the dominance of phonological coding strategies. The lack of evidence for phonological coding in the forward-recall condition shows that the preferential route for the Corsi blocks span task is to construct a visuospatial short-term representation in a similar way as verbal stimuli are stored phonologically.

At a theoretical level, the different pattern of results between forward and backward-recall implies that the forward-recall procedure yields a better or more pure measure of VSSP capacity than the backward-recall variant, because no phonological recoding was evident in forward-recall. Similarly, for clinical usage, this finding implies that the standard forward-recall version of the task is probably more appropriate than the backward-recall version to assess visuospatial capabilities of patients. Nevertheless, it should be kept in mind that executive control processes always play a rôle in the visuospatial span measured with the Corsi blocks procedure. In verbal tasks, the effect of the random-interval generation task, for example, disrupts performance of long sequences only (Vandierendonck *et al.*, 1998a), while in the present study, the effects were also clearly present at sequences of intermediate length. This is consistent with the claim which has been made several times that the visuospatial sketch pad might depend more strongly on the central executive than does the phonological loop (e.g. Baddeley, Cocchini, Della Sala, Logie, & Spinnler, 1999).

Concerning the difference between forward and backward-recall, it is also worth noting that under backward-recall instructions, the proportion of elements recalled in their correct serial position seems to be higher than under forward-recall instructions. Especially with longer sequences, this tendency became apparent. To our knowledge, no similar effects have been documented for verbal span tasks. In view of findings which show that visuospatial working-memory can maintain up to four separate object units (Wheeler & Treisman, 2002), it may be the case that a temporal order representation can be more easily reversed in visuospatial working-memory than in the phonological loop.

With respect to the random-time-interval generation task, the present findings also add to the converging picture arising from different applications of this task. First, the impact of the random-interval generation task, both in a visuospatial working-memory context (present study) and in a verbal short-term memory context (Vandierendonck *et al.*, 1998a), is similar and is obtained independently from the task content. Second, the fixed-interval generation task did not have any adverse effects on recall performance, either in the visuospatial or in the verbal domain. This observation is important because the fixed-interval generation task is, in all respects, similar to the random-interval generation task, except for the requirement to produce random-intervals. The difference between the effects of random-interval and fixed-interval generation must therefore be attributed completely to the random component of the random-interval generation task. Conceptually, this provides a strong basis for the claim that the random-interval generation task calls on executive processes.

Consistent with the finding that the effects of the random-interval generation task are domain-independent, Martein *et al.* (1999) reported that in a short-term double span task, in which both the content and location of a sequence of stimuli had to be memorized, the random-interval generation task impaired performance mainly when a coordinated recall of both components was required. All these findings further support the claim that the random-interval generation task does not tap the resources of the two slave systems. It may be suggested that the task calls on another as-yet unspecified slave system (for temporal events such as rhythms, for example, or the recently postulated episodic buffer; Baddeley, 2000). Overall, however, the findings are more in line with the interpretation that the task loads the central executive. In favour of this view, it has been found that the random-interval generation task affects the number of stimulus-independent thoughts (Stuyven & Van der Goten, 1995), interferes with intentional saccades (Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000), and impairs performance on simple arithmetic tasks both in a sum-verification paradigm (De Rammelaere, Stuyven, & Vandierendonck, 1999, 2001) and in a sum-production paradigm (De Rammelaere & Vandierendonck, 2001). Moreover, it has been shown that the randomness aspect of the task is critically important, in the present study, as well as in studies of verbal short-term memory (Vandierendonck *et al.*, 1998a) and judgment of randomness of time sequences (Vandierendonck, 2000c).

It may be said, then, that the present study has accumulated further evidence for the view that the random-interval generation task loads the central executive. However, the concept of central executive is multifaceted, and it is probably not the case that the random-interval generation task interferes with all of these facets. Miyake *et al.* (2000), for example, distinguish the functions of task-set shifting, memory updating, and inhibition of irrelevant responses. They showed, on the basis of structural equation modelling and confirmatory factor analysis, that random-number generation calls on the functions of shifting and updating. To the extent that the random-interval generation task shares features with the random number generation task, it may be expected that the task calls on the same functions. In a theoretical model of the components involved in random-interval generation, Vandierendonck (2000b) also postulates a monitoring function which would explain the difference between random-interval and fixed-interval generation. Whether monitoring, shifting, updating and possibly other executive processes are involved in random-interval generation is an issue for further research in the context of a strategy of fractionation of the executive (see also Baddeley, 1996).

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