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RESEARCH ARTICLE

# Response selection in dual task paradigms: observations from random generation tasks

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**Abstract** Performance of attention-demanding tasks is worse if two tasks are carried out simultaneously than if each of the tasks is performed alone. Our aim was to determine whether these 'dual task costs' can be attributed to mechanisms on a supra-trial level such as switching of limited resources between trials or concurrent breakdown of supervisory functions, or to mechanisms effective within each trial such as demands of response selection. Twenty healthy volunteers performed verbal random number generation (RNG) and random movement generation (RMG) at three different rates. For each rate, both tasks were examined once in a single task condition and once in a dual task condition. Results showed that performance (quality of randomness) in each random generation task (RNG/RMG) was reduced at faster rates and impaired by concurrent performance of a secondary random generation task. In the dual task condition, transient increase or decrease of bias in one random generation task during any short interval was not associated with concurrent increase or decrease of bias in the other task. In conclusion, the fact that during dual task performance transient bias in one task was not associated with concurrent improvement of performance in the other task indicates that alternation of supervisory control or attentional resources from one to the other task does not mediate the observed dual task costs. Resources of the central executive are not re-allocated or 'switched' from one to the other task. Dual task costs may result from mechanisms effective within each trial such as the demands of response selection.

**Keywords** Random generation · Willed action · Working memory · Response selection under conflict · Dual task

## Introduction

The working memory model of Baddeley et al. (1998) is a hierarchical concept of executive control over actions and mental processes designed to explain how the performance of routine and non-routine behavior required in daily life might be organized. In its current version, it encompasses separate storage modules for verbal and non-verbal information, the phonological loop and the visuospatial sketchpad. These are supplemented by a multimodal store, the episodic buffer, capable of integrating verbal and visuospatial information into one unitary episodic representation (Repovš and Baddeley 2006). According to this updated model, routine actions are performed automatically and accomplished by 'contention schedulers'. These are low-level control units, several of which can operate in parallel. We can, therefore, perform two or more very simple tasks at the same time without conflict between different action schemas as long as none of these tasks requires supervisory control. Non-routine actions demand attentional control and supervision, and are coordinated by the central executive. Whereas there are several contention schedulers, there is only one central executive. The central executive has limited capacity and it is posited that if two or more processes require supervision, the resources of the central executive have to be either shared between the two

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tasks or the two tasks are supervised in a serial fashion. The concurrent performance of two complex tasks is, therefore, just possible at the expense of the quality or speed of performance in one or both tasks.

Random generation is a complex task engaging a number of executive processes. Participants are provided with a response set, e.g., eight possible movements or number words 1–9, and instructed to produce sequences of items without any underlying order in pace with an external stimulus. This task requires permanent supervisory control for trial-by-trial decision-making, inhibition of habitual responses, switching of response strategies, and shift of attentional focus (Jahanshahi and Dirnberger 1999). Despite all efforts, sequences generated by human subjects are always biased and show several prepotent stereotypies such as avoidance of immediate repetitions and a tendency to overexpress adjacent responses (Baddeley et al. 1998; Brugger 1997; Brown et al. 1998). The magnitude of most types of bias becomes stronger with faster rates (Jahanshahi et al. 2000; Robertson et al. 1996) and is greater in patients with neurological diseases than in healthy controls (e.g., Annoni and Pegna 1997; Brugger et al. 1996; Dirnberger et al. 2005; Spatt and Goldenberg 1993), suggesting that non-randomness reflects the limitation of processing capacity rather than an erroneous concept of randomness.

Studies using dual task methodology have shown that random generation of letters (Baddeley et al. 1998; Robertson et al. 1996) or numbers (Brown et al. 1998; Evans 1980) interferes with the concurrent performance of a secondary attention-demanding task such as card sorting or visual tracking, particularly if this secondary task loads on working memory (Towse and Valentine 1997). Similarly, random movement generation (RMG) also shows the strongest interference if the secondary task requires a change of attentional set or switching. For example, the concurrent performance or a verbal fluency task that involves alternation between categories or a verbal analog of the trail making test necessitating alternation between letters and numbers interferes with RMG (Baddeley et al. 1998). It was subsequently suggested that ‘switching’ is a major source of dual task interference (Baddeley et al. 1998), but the precise scope and nature of switching (e.g., switching of strategy, of attention) are still under debate (Repovš and Baddeley 2006).

According to this ‘switching’ hypothesis, whenever the central executive is engaged in one task, it cannot attend to the other task as well. The behavioral consequence of this would be alternation of supervisory resources between the two tasks. Good performance in one task would be accompanied by inferior performance in the other, and vice versa (Fig. 1). According to a contrasting hypothesis, concurrent breakdown of supervisory control, the quality of randomness would deteriorate concurrently in both random generation tasks when the capacity of the central executive is exceeded and recover in parallel just when it is restored again. Finally, if the higher demands on the central executive during dual task performance result from trial-by-trial response selection, then the co-occurrence of bias in the two random generation tasks should be mere coincidence and occur at chance level.

The aim was to test these three alternative concepts of central executive failure in dual task performance. We tested these hypotheses with random number generation (RNG) performed concurrently to RMG compared to either task performed alone.

## Methods

### Participants

Twenty subjects (12 males) aged 22–53 years (mean ± SD, 31 ± 9 years) took part in the study. All subjects were right handed (Oldfield 1971) and had no history of psychiatric or neurological disease. Informed consent was obtained from all participants following the guidelines of the local Ethics Committee in accordance with the Declaration of Helsinki.

### Experimental design

Subjects performed two tasks: verbal RNG and motor RMG. Each task was performed at three different rates: requiring a response once every 0.5, 1.0, or 2.0 s. The RNG and RMG tasks were performed either in a single task condition or in a dual task condition concurrently with the other task (RNG or RMG, respectively). In all conditions, subjects generated 100 numbers, movements, or numbers and movements simultaneously. In the dual task conditions, RNG and RMG were always performed at the same rate. There were a total of nine conditions: (1) RNG rate 0.5 s, (2) RNG rate 1.0 s, (3) RNG rate 2.0 s, (4) RMG rate 0.5 s, (5) RMG rate 1.0 s, (6) RMG rate 2.0 s, (7) dual task rate 0.5 s, (8) dual task rate 1.0 s, (9) dual task rate 2.0 s. The order of conditions was counterbalanced across subjects.

### Procedure

The concept of randomness was first explained for the verbal RNG task using a hat analogy. Subjects were told to imagine that the numbers 1–9 are written on separate pieces of paper and placed in a hat and that they are taking out one piece of paper, calling out the number on it and returning it to the hat. Then they would reach for another piece of paper and call out the number written on it and so on. The series of numbers called out in this way would be random. For the RMG task, participants were instructed to make finger movements in the same fashion, using the index, middle, ring and little fingers of their left and right hands. Participants were instructed to synchronize their verbal and motor responses with a pacing LED flashing at a rate of 0.5, 1.0, or 2.0 s. The total time taken to complete a series of 100 responses was recorded for each task, rate, and condition. Participants were informed that it was most important to keep pace with the LED while at the same time they should always attempt to make their responses in both random generation tasks as random as possible. They were also instructed that both tasks were equally important. This procedure ensured that explicit instructions and implicit constraints did not prioritize one task over the other so that dual task costs in either task resulted from the subjects' own strategies and intrinsic limitations in concurrently processing two complex executive tasks (Levy and Pashler 2001; Ruthruff et al. 2003).

The verbal responses in the RNG task were tape recorded. The motor responses in the RMG task were detected with two response boxes for the left and right hands. Each of these boxes had four buttons that could be reached comfortably with the index, middle, ring and little fingers of the left or right hand. Each button was assigned to one particular finger of each hand. Subjects were instructed to rest their fingers on the appropriate buttons, but not to look at their fingers during testing. All responses made in the RNG or RMG task were recorded and stored for later analysis. In the design of our study, it was relevant that participants could choose their strategies freely and maintain them for any duration they wished, whether for just one trial or for an entire sequence.

### Standard measures of randomness

For the purpose of this study, it was important that measures of randomness reflected the specific types of bias that occur in verbal and motor random generation tasks. We obtained the following standard measures of randomness by considering the dependence structure of the relationship between items in a series:

1. Count Score 1 (CS1) measures the tendency to count in ascending or descending series in steps of one, e.g., 1-2-3 (Spatt and Goldenberg 1993). For the motor task, the equivalent to counting in steps of one is the use of adjacent fingers, e.g., left middle finger followed by left index finger. In calculating the count scores, the sequence length is squared to give higher weights to longer runs. Therefore, the above example would give a count score of $2^2 = 4$. Individuals may have a count score that is lower than predicted from a random series if they avoid certain counting tendencies or they may have a count score which is too high if they are unable to suppress counting.
2. The Mirroring Index (MIR) is a measure for use of homologous elements of an ordered set. In paradigms with an uneven set size, the middle item (the number 5 in our RNG task) has no homolog and does not contribute to this score. However, whenever subjects make symmetric jumps over the middle item, this counts as an MIR index of 1. Runs are not weighted. As an example, left index finger followed by right index finger counts as a MIR index of 1, and in the verbal task 1–9 counts as 1 and 2-8-2 counts as 2.
3. The Alternation Index (ALT) is a measure for alternation between the upper and lower half of an ordered set. For verbal RNG, transitions from any item smaller than the middle item to any item bigger than the middle item count as an ALT index of 1. Runs are not weighted, and in paradigms with an uneven set size, use of the middle item does not contribute to this score. For example, left index finger followed by any finger of the right hand counts as an ALT index of 1, and in the verbal task 4–9–3 counts as 2.
4. The Chi-square (CHI) statistic is a test of the frequency distribution which provides an index of response preference for any particular number or finger (Rosenberg et al. 1990).
5. The Random Generation Index (RGI) reflects any disproportion of diagrams in the matrix adjusted for disproportions in the marginal cell frequencies (Evans 1978). It varies between 0 and 1. The higher the index the less random the series is.

To allow comparison of these measures of randomness across the verbal and motor tasks, the data were standardized for each task through comparison with the mean of 10,000 computer-generated pseudo-random series of the same size (Dirnberger et al. 2005).

### Alternation of resources

It was of particular relevance to detect whether in the dual task condition participants would change their allocation of resources from one random generation task to the other one or several times in a series. For example, participants could initially focus their attention on the RNG task for some trials and maintain a higher level of randomness in their verbal output. This could happen at the expense of the quality of randomness in the concurrently performed RMG task. After some trials, participants might then change their strategy and focus attention on the motor task instead. This would improve the quality of randomness in the RMG task, whereas the quality of randomness in the verbal task would deteriorate. Such alternations between the verbal and motor domain might be repeated several times during the dual task condition.

If in the dual task condition participants change between modalities of random generation, the finding in the overall series would be a lower quality of randomness in both the verbal and the motor task compared to single task performance. However, if in the dual task condition subjects run out of some limited resource that is allocated to both tasks simultaneously, the analysis of the overall series would show the same result. Analysis of the overall series alone therefore cannot differentiate between alternation costs and other mechanisms of failing supervisory control on a supra-task level. A difference could only be detected from the analysis of subsequences or chunks of the individual series. If subjects alternate between tasks, better quality of randomness in one modality should be associated with worse quality in the other. In contrast, if dual task costs are due to failure of another mechanism as, e.g., temporary breakdown of supervisory control across tasks, then quality of randomness in the verbal and motor subsequences should deteriorate in parallel during episodes of fading supervision.

In order to discriminate effects of alternation from decrements in performance due to the limitation of supervisory resources, it is important to analyze the interrelationship of verbal and motor dual task series. Fortunately, the most prominent types of bias for the two tasks, counting for RNG and mirroring/alternating for RMG, occur from one to the next trial and can be calculated for every pair in a sequence. For a series of 100 numbers in the verbal task, there are consequently 99 measures of pairwise seriation analogous to CS1. This measure of pairwise seriation in RNG was labeled $\mathrm{CS1}_{\mathrm{pair}}$. Similarly, for a series of 100 movements in the motor task, there are 99 measures of pairwise mirroring and 99 measures of pairwise alternation calculated from one to the next movement. These measures of pairwise mirroring and alternation in RMG were labeled $\mathrm{MIR}_{\mathrm{pair}}$ and $\mathrm{ALT}_{\mathrm{pair}}$, respectively. As a next step, co-occurrence between transient bias in the verbal and motor tasks was calculated. Concurrent occurrence of two forms of bias was tested: $\mathrm{CS1}_{\mathrm{pair}}$ with $\mathrm{ALT}_{\mathrm{pair}}$ and $\mathrm{CS1}_{\mathrm{pair}}$ with $\mathrm{MIR}_{\mathrm{pair}}$. For each series, the number of trials where transient bias occurred concurrently in both tasks (RNG and RMG), only in the RNG task, only in the RMG task, or in none of the two tasks was calculated. The resulting scores were square-root transformed to approximate a parametric distribution for subsequent statistical tests.

In simple terms, the purpose of this statistical analysis was to compare the frequency of occurrence of pairwise bias in the dual task condition to the frequency of pairwise bias in the single task conditions. In this comparison, any 'association' of bias in the single task conditions would occur by chance and represent baseline level. If the hypothesis that dual task costs are due to alternating allocation of resources is supported, then the frequency of occurrence of pairwise bias in the dual task condition would be smaller than in the single tasks. There would be a tendency for bias either in the verbal or in the motor task, but not at the same time in both tasks. In contrast, if supervisory resources concerned with simultaneous control of the verbal and motor output are 'overloaded' or exceeded in the dual task condition, then the hypothesis would be that, since this occurs at the same time for both tasks, the frequency of occurrence of pairwise bias for the dual task condition would be higher than for the single tasks. In this case, there would be a tendency for concurrent bias in the verbal and motor tasks, which would be stronger than for the single verbal or motor tasks performed alone. If, however, the two random generation tasks are relatively independent (as in the case of a response selection conflict involving competition between tasks), then the co-occurrence of verbal and motor bias in the dual task condition should be mere coincidence and about the same as for sequences from the single task conditions (Fig. 1).

## Data analysis

Five repeated-measures analyses of variance (ANOVAs) were carried out separately for each standard (*z* score) measure of randomness (CS1, MIR, ALT, CHI, RGI). Each ANOVA used TASK (RMG vs. RNG), LOAD (single task vs. dual task condition) and RATE (response intervals 0.5, 1.0, or 2.0 s) as within-subject factors. One repeated-measures ANOVA with the same within-subject factors was calculated on the time required to produce the 100 numbers or movements. Time was square-root transformed to achieve a parametric distribution.

Separate ANOVAs were calculated for the analysis of alternation to test associations of counting in RNG with mirroring or alternation of hands in RMG. These ANOVAs were calculated on the square-root transformed scores of bias with the within-subject factors LOAD (single task vs. dual task condition) and RATE (response intervals 0.5, 1.0, or 2.0 s) on the percentage of trials with $\mathrm{CS1}_{\mathrm{pair}}$ (RNG trials with or without counting from the previous to the present trial) with $\mathrm{MIR}_{\mathrm{pair}}$ (RMG trials with or without mirroring from the previous to the present trial) and $\mathrm{CS1}_{\mathrm{pair}}$ with $\mathrm{ALT}_{\mathrm{pair}}$ (RMG trials with or without alternation of hands from the previous to the present trial) measures. For subsequent single-subject analyses, chi-squared comparisons were calculated on the same scores of paired bias ($\mathrm{CS1}_{\mathrm{pair}}/\mathrm{MIR}_{\mathrm{pair}}$ and $\mathrm{CS1}_{\mathrm{pair}}/\mathrm{ALT}_{\mathrm{pair}}$) separately for each subject, task and rate in order to test whether bias in the verbal and motor tasks is perhaps just associated in some subjects.

For all ANOVAs, Greenhouse–Geisser corrected *F* values are reported for within-subject factors with more than two levels, and the level of significance was set to

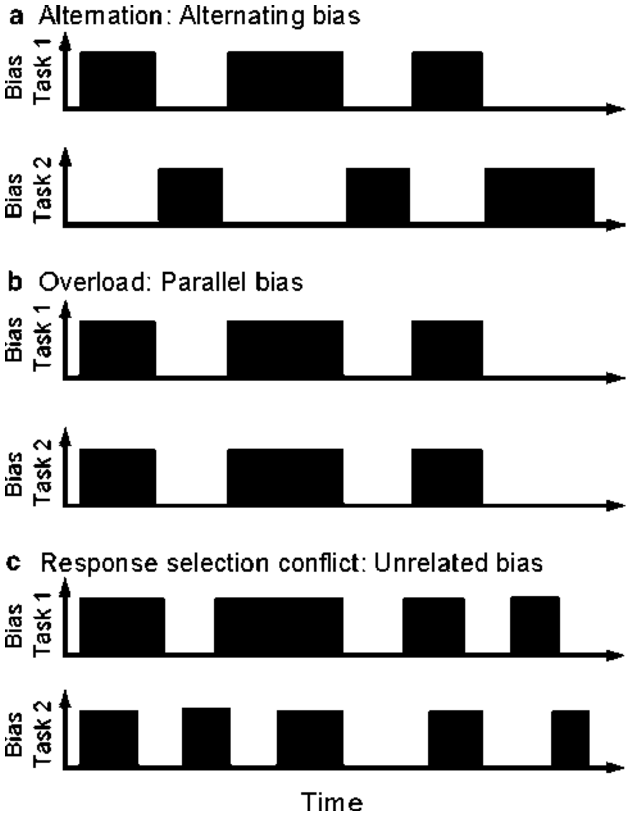

**Fig. 1** Schematic representation of alternative hypotheses. According to the alternation hypothesis (**a**), the allocation of supervisory control is changed between tasks. Good (unbiased) performance in one task is accompanied by inferior (strongly biased) performance in the other, and vice versa. According to the overload hypothesis (**b**), a resource limitation may occur simultaneously in both tasks, and performance consequently deteriorates for both tasks in parallel. In case of a response selection conflict (**c**), performance in each task has no temporal relationship to performance in the other task. For the sake of simplicity, response bias is shown as a dichotomous variable

$p = 0.05$. A Bonferroni correction was applied to the multiple comparisons of the single-subject analysis, and the corrected level of significance was set to $p = 0.0004$.

## Results

### Effects of rate and load on total time to complete tasks

As expected, the total time required to produce the 100 numbers or movements decreased with faster rates as indicated by a significant main effect of RATE ($F(2, 38) = 18590.00$; $\varepsilon = 0.77$, $p < 0.01$). The main effects of TASK and LOAD were not significant. The significant TASK × LOAD interaction ($F(1, 19) = 36.20$; $p < 0.01$) was explained by longer (less accurate) response rates in RMG but not in RNG for the dual task compared to the single task condition. A significant TASK × RATE interaction ($F(2, 38) = 29.05$; $\varepsilon = 0.72$, $p < 0.01$) was explained by a stronger effect of rate on RMG compared to RNG which was mainly due to slowed (less accurate) performance at the fastest RNG rate. A three-way interaction TASK × RATE × LOAD ($F(2, 38) = 18.26$; $\varepsilon = 0.66$, $p < 0.01$) resulted from a specific effect at the fastest rate: whereas completion times were most similar across the two random generation tasks in the dual task condition (RNG: 535 ± 60 ms, RMG: 539 ± 66 ms), RMG performance was faster in the single task condition (478 ± 34 ms) whereas the reverse was true for RNG (547 ± 46 ms).

### Effects of rate and load on standard measures of randomness

For CS1, the significant main effect of TASK ($F(1, 19) = 14.96$; $p < 0.01$) was explained by higher scores in the verbal RNG task than in the motor RMG task. The significant main effect of RATE ($F(2, 38) = 31.64$; $\varepsilon = 0.84$, $p < 0.01$) indicated that as expected for both the verbal and the motor tasks, CS1 increased with faster rates. The main effect of LOAD was not significant. The significant TASK × LOAD interaction ($F(1, 19) = 22.10$; $p < 0.01$) indicated that for the RNG task, CS1 scores were higher in the dual task than in the single task condition ($F(1, 19) = 12.98$; $p < 0.01$), whereas there was a slight but significant decrease of CS1 from single to dual task for the RMG task ($F(1, 19) = 13.20$; $p < 0.01$; Fig. 2a). Differences in CS1 between the RNG and RMG tasks were significantly greater for the dual than the single task condition. The significant TASK × RATE interaction ($F(2, 38) = 12.69$; $\varepsilon = 0.81$, $p < 0.01$) was explained by a much stronger increase of CS1 with faster rates in the RNG task ($F(2, 38) = 35.22$; $\varepsilon = 0.87$, $p < 0.01$) compared to the RMG task ($F(2, 38) = 7.24$; $\varepsilon = 0.84$, $p < 0.01$; Fig. 2b). The RATE × LOAD and TASK × RATE × LOAD interactions were not significant.

For the MIR index, a significant main effect of TASK ($F(1, 19) = 64.23$; $p < 0.01$) indicated that scores were higher for the motor RMG than for the verbal RNG task. A significant main effect of RATE ($F(2, 38) = 5.67$; $\varepsilon = 0.69$, $p = 0.05$) was explained by higher MIR scores at faster rates. The main effect of LOAD was not significant. The significant TASK × RATE interaction ($F(2, 38) = 25.18$, $\varepsilon = 0.78$, $p < 0.01$) indicated that MIR scores increased significantly with faster rates in the RMG task ($F(2, 38) = 16.07$; $\varepsilon = 0.83$, $p < 0.01$) but decreased with faster rates in the RNG task ($F(2, 38) = 3.37$; $\varepsilon = 0.87$, $p < 0.05$; Fig. 3). The TASK × LOAD, RATE × LOAD and TASK × RATE × LOAD interactions were not significant.

For the ALT index, a significant main effect of TASK ($F(1, 19) = 39.00$; $p < 0.01$) was explained by higher scores in the motor RMG task than in the verbal RNG task.

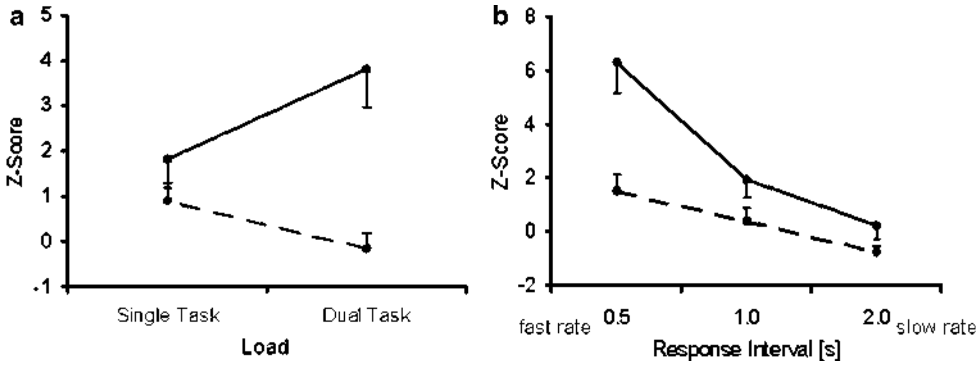

**Fig. 2** **a** The effect of load (single vs. dual task condition) on count score 1 (CS1) in the random movement generation (*broken line*) and random number generation (*solid line*) tasks. Data are collapsed across rate. *Error bars* indicate standard error. **b** Effect of rate of the pacing stimulus on count score 1 (CS1) in the random movement generation (*broken line*) and random number generation (*solid line*) tasks. Data are collapsed across load. *Error bars* indicate standard error

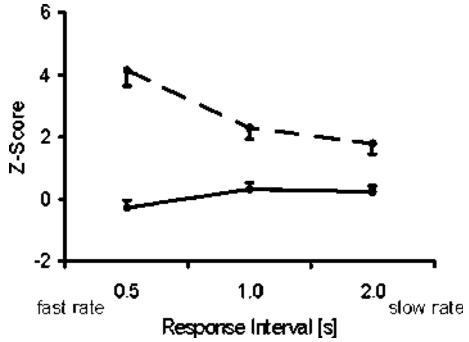

**Fig. 3** Effect of rate of the pacing stimulus on the mirroring index (MIR) in the random movement generation (*broken line*) and random number generation (*solid line*) tasks. Data are collapsed across load. *Error bars* indicate standard error

The main effects of LOAD and RATE were not significant. The significant TASK × LOAD interaction ($F(1, 19) = 37.66$; $p < 0.01$) indicated that for the RMG task, ALT scores were significantly higher in the dual task compared to the single task condition ($F(1, 19) = 15.91$; $p < 0.01$), whereas for the RNG task scores were significantly higher in the single task compared to the dual task condition ($F(1, 19) = 26.36$; $p < 0.01$; Fig. 4a). Furthermore, differences in ALT between the RNG and RMG tasks became significantly greater for the dual than the single task condition. The significant TASK × RATE interaction ($F(2, 38) = 11.13$; $\varepsilon = 0.78$, $p < 0.01$) indicated that ALT scores decreased significantly with faster rates in the RNG task ($F(1, 19) = 26.48$; $p < 0.01$) but not in the RMG task (Fig. 4b). The RATE × LOAD and TASK × RATE × LOAD interactions were not significant.

In the ANOVA analysis of CHI, a significant main effect of TASK ($F(1, 19) = 76.71$; $p < 0.01$) was explained by higher scores in the motor RMG task than in the verbal RNG task. A main effect of LOAD ($F(1, 19) = 29.51$; $p < 0.01$) was associated with higher scores in the dual task compared to the single task condition. A main effect of RATE ($F(2, 38) = 5.95$; $\varepsilon = 0.70$, $p < 0.05$) was explained by higher CHI scores at faster rates. The TASK × LOAD interaction ($F(1, 19) = 6.47$; $p < 0.01$) indicated that for the RMG task, CHI scores were

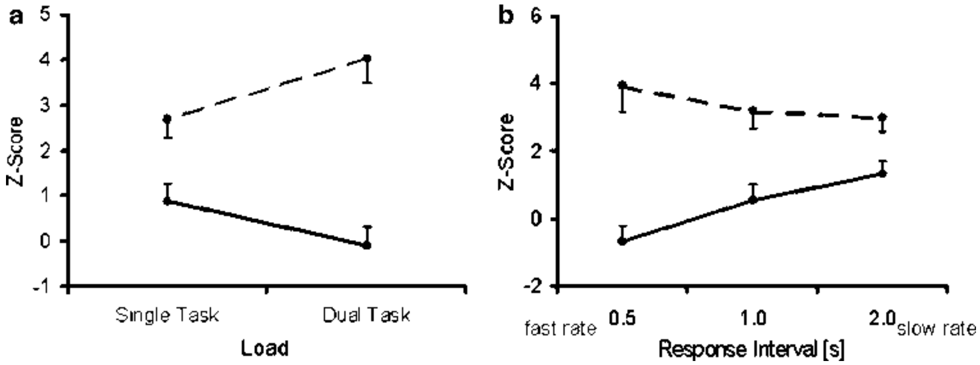

**Fig. 4** **a** The effect of load (single vs. dual task condition) on the alternation index (ALT) for random movement generation (broken line) and random number generation (*solid line*). Data are collapsed across rate. *Error bars* indicate standard error. **b** Effect of rate of the pacing stimulus on the ALT in the random movement generation (*broken line*) and random number generation (*solid line*) tasks. Data are collapsed across load. *Error bars* indicate standard error

significantly higher in the dual task compared to the single task condition ($z$ scores 2.98 ± 0.46 vs. 0.88 ± 0.16; $F(1, 19) = 26.23$; $p < 0.01$), whereas for the RNG task this significant increment was smaller ($z$ scores 0.34 ± 0.28 vs. −0.30 ± 0.18; $F(1, 19) = 8.69$; $p < 0.05$). The other interactions were not significant.

In the ANOVA analysis of RGI, a main effect of TASK ($F(1, 19) = 46.00$; $p < 0.01$) was explained by higher scores in the motor RMG task than in the verbal RNG task. A main effect of LOAD ($F(1, 19) = 30.06$; $p < 0.01$) was associated with higher scores in the dual task compared to the single task condition. A main effect of RATE ($F(2, 38) = 40.63$; $\varepsilon = 0.69$, $p < 0.01$) was explained by higher RGI scores at faster rates. The TASK × LOAD interaction ($F(1, 19) = 8.48$; $p < 0.01$) indicated that the increase in the dual task condition compared to the single task condition is higher in the motor RMG task ($z$ scores 5.58 ± 0.52 vs. 3.93 ± 0.32; $F(1, 19) = 22.77$; $p < 0.01$) than in the verbal RNG task ($z$ scores 2.51 ± 0.24 vs. 2.03 ± 0.18; $F(1, 19) = 6.20$; $p < 0.05$). The other interactions were not significant.

### Analysis of alternation

The first analysis of alternation focused on verbal counting and movement mirroring. Here, the interactions LOAD × $\mathrm{CS1}_{\mathrm{pair}}$ × $\mathrm{MIR}_{\mathrm{pair}}$ and LOAD × RATE × $\mathrm{CS1}_{\mathrm{pair}}$ × $\mathrm{MIR}_{\mathrm{pair}}$ were both not significant. This indicates that for the dual task condition across rates and for any particular rate, transient counting bias during RNG was not associated with higher or lower mirroring bias in RMG in the same trial, and vice versa. Similar results were obtained for the other alternation analysis focused on verbal counting and movement alternation where the respective interaction effects LOAD × $\mathrm{CS1}_{\mathrm{pair}}$ × $\mathrm{ALT}_{\mathrm{pair}}$ and LOAD × RATE × $\mathrm{CS1}_{\mathrm{pair}}$ × $\mathrm{ALT}_{\mathrm{pair}}$ were also not significant.

Figure 5 compares the percentage of trials with transient associated and non-associated $\mathrm{CS1}_{\mathrm{pair}}/\mathrm{MIR}_{\mathrm{pair}}$ or $\mathrm{CS1}_{\mathrm{pair}}/\mathrm{ALT}_{\mathrm{pair}}$ bias, separately for the single task condition and for the dual task condition. For both conditions, the expected frequencies of associated transient bias were calculated under the assumption that bias in the verbal and motor task is independent. These expected frequencies are displayed as small arrows to the left and right of the respective columns showing the observed values. Differences between observed and expected frequencies are always less than 1%. The results, therefore, indicate that for all rates, and for the single task conditions as well as for the dual task condition, transient counting bias in RNG is independent from concurrent mirroring or alternation bias in RMG. For RNG as well as for RMG, bias in the dual task condition is stronger than in the single task condition, but this increase of bias does not depend on whether there is bias in the other response modality in the same trial. Subsequent single-subject analyses confirmed that for all participants there were no significant associations between transient bias in the RNG and RMG task (Tables 1, 2).

## Discussion

To summarize the main results: (1) Verbal and motor random generation are dominated by different types of bias. A bias towards adjacent responses (counting) is more pronounced in RNG than the analogous bias (use of adjacent fingers) in RMG. In contrast, a bias towards mirroring (use of homologous fingers of the two hands) and alternation between left and right hands is stronger for RMG than an analogous bias for RNG. In addition, the frequency distribution of the output as indexed by the CHI and RGI measures was more biased for the RMG than the RNG task. (2) For each task, the effects of rate are most evident for the dominant type of bias. With faster rates, there is a significant increase of counting in RNG but only a moderate increase for the analogous use of adjacent fingers in RMG. Similarly, with faster rates, there is a pronounced increase of alternations in RMG but not for the analogous bias (responses from the upper and lower half of the set) in RNG. (3) Performance in a verbal or motor random generation task becomes worse, i.e., more non-random by concurrent performance of a secondary random generation task in another modality. Again, for each task, the effects of dual task performance are most evident for the dominant type of bias. For RNG, counting in the dual task condition was higher (less random output) than in the single task condition, whereas the analogous use of adjacent fingers in RMG was not affected in the same way. For RMG, alternation of hands was higher (less random output) in the dual task than in the single task condition, whereas the analogous bias in RNG (responses from the upper and lower half of the set) was not. (4) For the dual task condition, transient change of bias in one random generation task is not associated with a concurrent increase or decrease of bias in the other random generation task. Subsequent analyses confirmed the lack of any association of bias even at the single participant level, indicating that the absence of an overall association was not due to individual subjects using different strategies. (5) For both RMG and RNG, the two experimentally manipulated variables, rate and load, generally produced similar effects on the measures of randomness.

### Response rate in verbal and motor random generation

A significant reduction of RNG response rate during concurrent performance of a pegboard task with the non-dominant hand has been described as the only change

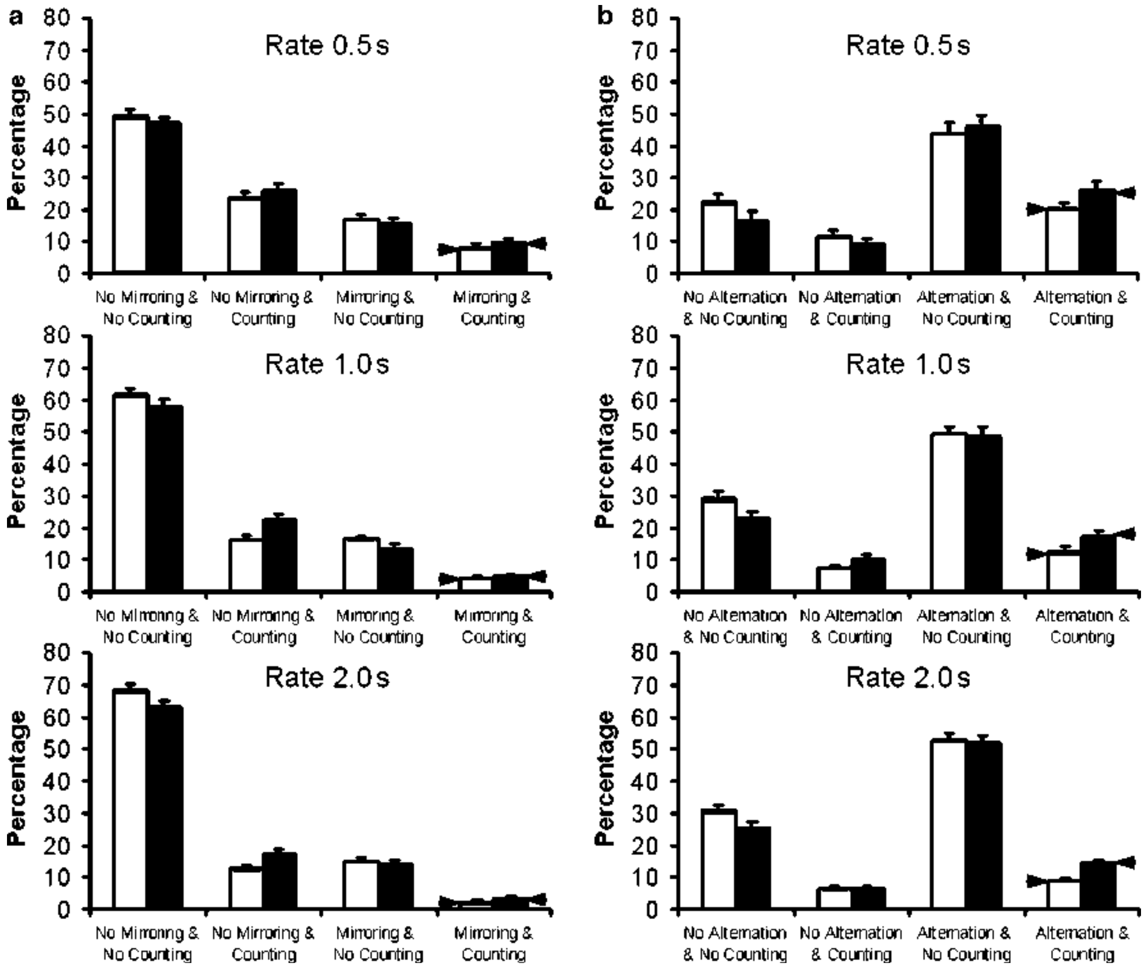

**Fig. 5** The percentage of trials with or without concurrent transient bias in the verbal (RNG) and motor (RMG) random generation task. Transient bias was measured from the previous to the current trial. Column **a** displays data with or without concurrent occurrence of counting (CS1$_{pair}$) in RNG with mirroring (MIR$_{pair}$) in RMG. Column **b** displays data with or without concurrent occurrence of counting (CS1$_{pair}$) in RNG and alternation of hands (ALT$_{pair}$) in RMG. For each column, separate diagrams are shown for each of the three different rates. *White bars* represent the single task, and *black bars* represent the dual task condition. *Error bars* indicate standard errors. The expected frequencies of associated transient bias were calculated under the assumption that bias in the verbal and motor tasks is independent, and are displayed as *small arrows* to the *left* and *right* of the respective *columns*. This shows that there is virtually no difference between expected and observed association of transient bias. Response bias is, therefore, independent in the motor and verbal task, with associations of transient bias occurring just at chance level

during RNG in a dual task situation with a secondary motor task (Strenge and Niederberger 2008). In our study, we found slowed performance (less accurate synchronization with the pacing stimulus) just at the fastest RNG rate across the single task and dual task condition whereas for RMG a specific acceleration effect (but no slowing) was seen at the fastest rate in the dual task condition. However, these results appear difficult to compare due to differences in the design and the instructions given to participants. The fastest rate in our study was two times faster than the most demanding rate used by Strenge and Niederberger (2008), and in our instructions we emphasized the importance of keeping pace with the stimulus. This emphasis may explain why participants in our experiment kept the intermediate (1 s) rate in the dual task condition more precisely than the participants in the study by Strenge and Niederberger (2008).

## Comparison of standard measures of randomness in verbal and motor random generation

The analysis of standard measures of randomness confirmed that the magnitude of each form of bias depends on the modality in which random generation was performed (Baddeley et al. 1998; Towse 1998). Some types of bias such as the avoidance of immediate repetitions are identical for verbal and motor tasks. The strongest patterns of stereotypy, however, depend on the output modality even if subjects receive precisely the same instructions for verbal and motor tasks. For verbal RNG, habitual counting is the

**Table 1** Association of transient counting bias ($\mathrm{CS1}_{\mathrm{pair}}$) in the random number generation task (RNG) and transient alternation of hands bias ($\mathrm{ALT}_{\mathrm{pair}}$) in the random movement generation task (RMG), separately for each subject (No. 1–20), load (single task vs. dual task condition) and rate (0.5, 1.0, and 2.0 s interval)

| No. | Single Task bias | | | | | | Dual Task bias | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Observed | | | | Expected | | Observed | | | | Expected | |
| | no $\mathrm{CS1}_{\mathrm{pair}}$ no $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ no $\mathrm{ALT}_{\mathrm{pair}}$ | no $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\chi^2_{df=1}$ | no $\mathrm{CS1}_{\mathrm{pair}}$ no $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ no $\mathrm{ALT}_{\mathrm{pair}}$ | no $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\mathrm{CS1}_{\mathrm{pair}}$ $\mathrm{ALT}_{\mathrm{pair}}$ | $\chi^2_{df=1}$ |
| Rate 0.5 s | | | | | | | | | | | | |
| 1 | 21 | 15 | 30 | 33 | 30.5 | 1.1 | 14 | 13 | 37 | 35 | 34.9 | 0.0 |
| 2 | 12 | 11 | 40 | 36 | 36.1 | 0.0 | 3 | 4 | 51 | 41 | 41.8 | 0.4 |
| 3 | 17 | 16 | 41 | 25 | 27.3 | 1.0 | 16 | 5 | 43 | 35 | 31.5 | 3.0 |
| 4 | 19 | 14 | 40 | 26 | 26.7 | 0.1 | 26 | 19 | 20 | 34 | 28.9 | 4.2 |
| 5 | 39 | 24 | 24 | 12 | 13.1 | 0.2 | 8 | 3 | 53 | 35 | 33.8 | 0.6 |
| 6 | 12 | 8 | 57 | 22 | 23.9 | 1.1 | 10 | 6 | 57 | 26 | 26.8 | 0.2 |
| 7 | 20 | 2 | 59 | 18 | 15.6 | 2.2 | 15 | 8 | 50 | 26 | 26.1 | 0.0 |
| 8 | 48 | 18 | 25 | 8 | 8.7 | 0.1 | 47 | 24 | 19 | 9 | 9.3 | 0.0 |
| 9 | 27 | 8 | 53 | 11 | 12.3 | 0.5 | 10 | 3 | 61 | 25 | 24.3 | 0.2 |
| 10 | 23 | 22 | 35 | 19 | 22.4 | 1.9 | 33 | 15 | 30 | 21 | 18.5 | 1.1 |
| 11 | 28 | 9 | 47 | 15 | 15.0 | 0.0 | 15 | 10 | 43 | 31 | 30.6 | 0.0 |
| 12 | 36 | 29 | 19 | 15 | 15.1 | 0.0 | 35 | 31 | 15 | 18 | 16.3 | 0.5 |
| 13 | 30 | 9 | 48 | 12 | 12.7 | 0.1 | 17 | 5 | 63 | 14 | 14.8 | 0.2 |
| 14 | 4 | 1 | 69 | 25 | 24.7 | 0.1 | 0 | 0 | 65 | 34 | 34.0 | na |
| 15 | 28 | 12 | 47 | 12 | 14.3 | 1.2 | 18 | 6 | 56 | 19 | 18.9 | 0.0 |
| 16 | 15 | 8 | 38 | 38 | 35.3 | 1.6 | 8 | 8 | 40 | 43 | 42.8 | 0.0 |
| 17 | 6 | 5 | 62 | 26 | 27.6 | 1.2 | 0 | 0 | 62 | 37 | 37.0 | na |
| 18 | 24 | 6 | 52 | 17 | 16.0 | 0.3 | 18 | 5 | 63 | 13 | 13.8 | 0.3 |
| 19 | 29 | 14 | 33 | 23 | 20.9 | 0.8 | 21 | 13 | 46 | 19 | 21.0 | 0.8 |
| 20 | 14 | 7 | 63 | 15 | 17.3 | 1.9 | 24 | 6 | 51 | 18 | 16.7 | 0.4 |
| Rate 1.0 s | | | | | | | | | | | | |
| 1 | 30 | 10 | 31 | 28 | 22.6 | 5.1 | 15 | 11 | 39 | 34 | 33.2 | 0.1 |
| 2 | 22 | 11 | 49 | 17 | 18.7 | 0.6 | 5 | 5 | 71 | 18 | 20.7 | 4.5 |
| 3 | 23 | 9 | 47 | 20 | 19.6 | 0.0 | 23 | 25 | 29 | 22 | 24.2 | 0.8 |
| 4 | 26 | 8 | 48 | 17 | 16.4 | 0.1 | 16 | 21 | 36 | 26 | 29.4 | 2.0 |
| 5 | 25 | 10 | 46 | 18 | 18.1 | 0.0 | 30 | 18 | 37 | 14 | 16.5 | 1.1 |
| 6 | 44 | 8 | 40 | 7 | 7.1 | 0.0 | 33 | 11 | 42 | 13 | 13.3 | 0.0 |
| 7 | 41 | 6 | 42 | 10 | 8.4 | 0.8 | 30 | 6 | 50 | 13 | 12.1 | 0.2 |
| 8 | 42 | 8 | 43 | 6 | 6.9 | 0.3 | 22 | 11 | 43 | 23 | 22.7 | 0.0 |
| 9 | 28 | 7 | 48 | 16 | 14.9 | 0.3 | 18 | 9 | 53 | 19 | 20.4 | 0.5 |
| 10 | 36 | 7 | 43 | 13 | 11.3 | 0.7 | 32 | 19 | 36 | 12 | 15.0 | 1.7 |
| 11 | 25 | 7 | 57 | 10 | 11.5 | 0.7 | 17 | 6 | 61 | 15 | 16.1 | 0.4 |
| 12 | 24 | 6 | 55 | 14 | 13.9 | 0.0 | 29 | 14 | 40 | 16 | 17.0 | 0.2 |
| 13 | 43 | 3 | 48 | 5 | 4.3 | 0.3 | 44 | 6 | 44 | 5 | 5.4 | 0.1 |
| 14 | 16 | 8 | 58 | 17 | 18.9 | 1.1 | 13 | 5 | 67 | 14 | 15.5 | 1.0 |
| 15 | 29 | 8 | 52 | 10 | 11.3 | 0.5 | 31 | 7 | 50 | 11 | 11.1 | 0.0 |
| 16 | 33 | 19 | 28 | 19 | 18.0 | 0.2 | 31 | 15 | 26 | 27 | 22.5 | 3.4 |
| 17 | 5 | 2 | 80 | 12 | 13.0 | 1.3 | 3 | 0 | 69 | 27 | 26.2 | 1.2 |
| 18 | 27 | 3 | 64 | 5 | 5.6 | 0.2 | 23 | 7 | 58 | 11 | 12.5 | 0.8 |
| 19 | 30 | 8 | 51 | 10 | 11.1 | 0.3 | 29 | 7 | 50 | 13 | 12.7 | 0.0 |
| 20 | 35 | 6 | 54 | 4 | 5.9 | 1.6 | 16 | 2 | 68 | 13 | 12.3 | 0.3 |
| Rate 2.0 s | | | | | | | | | | | | |
| 1 | 29 | 11 | 44 | 15 | 15.5 | 0.1 | 12 | 11 | 43 | 33 | 33.8 | 0.1 |
| 2 | 22 | 4 | 62 | 11 | 11.1 | 0.0 | 14 | 4 | 63 | 18 | 18.0 | 0.0 |
| 3 | 27 | 9 | 55 | 8 | 10.8 | 2.4 | 32 | 5 | 47 | 15 | 12.5 | 1.6 |
| 4 | 35 | 5 | 48 | 11 | 9.5 | 0.7 | 27 | 16 | 33 | 23 | 22.1 | 0.2 |
| 5 | 31 | 10 | 46 | 12 | 12.9 | 0.2 | 32 | 11 | 42 | 14 | 14.1 | 0.0 |
| 6 | 35 | 9 | 51 | 4 | 7.2 | 3.7 | 47 | 9 | 32 | 11 | 8.7 | 1.4 |
| 7 | 33 | 6 | 49 | 11 | 10.3 | 0.1 | 40 | 6 | 43 | 10 | 8.6 | 0.6 |
| 8 | 35 | 5 | 53 | 6 | 6.6 | 0.1 | 22 | 5 | 60 | 12 | 12.4 | 0.0 |
| 9 | 38 | 9 | 44 | 8 | 8.9 | 0.2 | 11 | 6 | 66 | 16 | 18.2 | 2.0 |
| 10 | 23 | 11 | 55 | 10 | 13.8 | 3.8 | 34 | 7 | 43 | 15 | 12.9 | 1.1 |
| 11 | 27 | 1 | 57 | 14 | 10.8 | 4.1 | 23 | 2 | 66 | 8 | 7.5 | 0.2 |
| 12 | 31 | 7 | 48 | 13 | 12.3 | 0.1 | 23 | 8 | 51 | 17 | 17.2 | 0.0 |
| 13 | 28 | 2 | 67 | 2 | 2.8 | 0.8 | 39 | 0 | 53 | 7 | 4.2 | 4.9 |
| 14 | 28 | 4 | 63 | 4 | 5.4 | 1.2 | 22 | 4 | 61 | 12 | 11.8 | 0.0 |
| 15 | 32 | 4 | 53 | 10 | 8.9 | 0.4 | 23 | 2 | 62 | 12 | 10.5 | 1.0 |
| 16 | 40 | 13 | 30 | 16 | 13.5 | 1.3 | 16 | 13 | 49 | 21 | 24.0 | 2.0 |
| 17 | 9 | 1 | 78 | 11 | 10.8 | 0.0 | 3 | 0 | 71 | 25 | 24.2 | 1.0 |
| 18 | 31 | 9 | 56 | 3 | 7.2 | 6.8 | 33 | 10 | 48 | 8 | 10.2 | 1.3 |
| 19 | 36 | 7 | 50 | 6 | 7.4 | 0.7 | 26 | 5 | 60 | 8 | 8.9 | 0.4 |
| 20 | 49 | 3 | 46 | 1 | 1.9 | 0.8 | 34 | 7 | 51 | 7 | 8.2 | 0.5 |

No., subject number; $\mathrm{CS1}_{\mathrm{pair}}$, RNG trials with or without counting from the previous to the present trial; $\mathrm{ALT}_{\mathrm{pair}}$, RMG trials with or without alternation of hands from the previous to the present trial. After Bonferroni correction for multiple comparisons, none of the associations is significant

**Table 2** Association of transient counting bias ($\mathrm{CS1}_{pair}$) in the random number generation task (RNG) and transient mirroring bias ($\mathrm{MIR}_{pair}$) in the random movement generation task (RMG), separately for each subject (No. 1–20), load (single task vs. dual task condition) and rate (0.5, 1.0, and 2.0 s interval)

| | Single Task bias | | | | | | Dual Task bias | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Observed | | | | Expected | | Observed | | | | Expected | |
| No. | no $\mathrm{CS1}_{pair}$ no $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ no $\mathrm{MIR}_{pair}$ | no $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\chi^2_{df=1}$ | no $\mathrm{CS1}_{pair}$ no $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ no $\mathrm{MIR}_{pair}$ | no $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\mathrm{CS1}_{pair}$ $\mathrm{MIR}_{pair}$ | $\chi^2_{df=1}$ |
| Rate 0.5 s | | | | | | | | | | | | |
| 1 | 40 | 41 | 11 | 7 | 8.7 | 0.8 | 44 | 36 | 7 | 12 | 9.2 | 2.0 |
| 2 | 33 | 29 | 19 | 18 | 17.6 | 0.0 | 36 | 27 | 18 | 18 | 16.4 | 0.5 |
| 3 | 40 | 24 | 18 | 17 | 14.5 | 1.1 | 39 | 27 | 20 | 13 | 13.3 | 0.0 |
| 4 | 36 | 26 | 23 | 14 | 14.9 | 0.2 | 38 | 39 | 8 | 14 | 11.8 | 1.2 |
| 5 | 51 | 30 | 12 | 6 | 6.5 | 0.1 | 43 | 21 | 18 | 17 | 13.4 | 2.4 |
| 6 | 43 | 19 | 26 | 11 | 11.2 | 0.0 | 43 | 22 | 24 | 10 | 11.0 | 0.2 |
| 7 | 65 | 12 | 14 | 8 | 4.4 | 4.6 | 51 | 23 | 14 | 11 | 8.6 | 1.4 |
| 8 | 61 | 23 | 12 | 3 | 3.9 | 0.4 | 60 | 31 | 6 | 2 | 2.7 | 0.3 |
| 9 | 54 | 14 | 26 | 5 | 5.9 | 0.3 | 46 | 16 | 25 | 12 | 10.5 | 0.5 |
| 10 | 45 | 31 | 13 | 10 | 9.5 | 0.1 | 50 | 30 | 13 | 6 | 6.9 | 0.2 |
| 11 | 54 | 17 | 21 | 7 | 6.8 | 0.0 | 41 | 29 | 17 | 12 | 12.0 | 0.0 |
| 12 | 45 | 39 | 10 | 5 | 6.7 | 0.9 | 44 | 45 | 6 | 4 | 4.9 | 0.4 |
| 13 | 69 | 16 | 9 | 5 | 3.0 | 2.1 | 58 | 14 | 22 | 5 | 5.2 | 0.0 |
| 14 | 50 | 19 | 23 | 7 | 7.9 | 0.2 | 45 | 22 | 20 | 12 | 11.0 | 0.2 |
| 15 | 57 | 16 | 18 | 8 | 6.3 | 0.8 | 46 | 20 | 28 | 5 | 8.3 | 2.7 |
| 16 | 41 | 37 | 12 | 9 | 9.8 | 0.1 | 39 | 36 | 9 | 15 | 12.4 | 1.5 |
| 17 | 45 | 21 | 23 | 10 | 10.3 | 0.0 | 44 | 27 | 18 | 10 | 10.5 | 0.0 |
| 18 | 58 | 19 | 18 | 4 | 5.1 | 0.4 | 67 | 14 | 14 | 4 | 3.3 | 0.2 |
| 19 | 52 | 28 | 10 | 9 | 7.1 | 1.0 | 52 | 26 | 15 | 6 | 6.8 | 0.2 |
| 20 | 51 | 19 | 26 | 3 | 6.4 | 3.3 | 56 | 17 | 19 | 7 | 6.3 | 0.1 |
| Rate 1.0 s | | | | | | | | | | | | |
| 1 | 54 | 28 | 7 | 10 | 6.5 | 3.6 | 44 | 33 | 10 | 12 | 10.0 | 0.9 |
| 2 | 52 | 23 | 19 | 5 | 6.8 | 0.9 | 47 | 22 | 29 | 1 | 7.0 | 9.6 |
| 3 | 50 | 23 | 20 | 6 | 7.6 | 0.7 | 44 | 41 | 8 | 6 | 6.6 | 0.1 |
| 4 | 57 | 19 | 17 | 6 | 5.8 | 0.0 | 40 | 37 | 12 | 10 | 10.4 | 0.0 |
| 5 | 58 | 22 | 13 | 6 | 5.4 | 0.1 | 61 | 24 | 6 | 8 | 4.5 | 4.6 |
| 6 | 71 | 14 | 13 | 1 | 2.1 | 0.8 | 68 | 21 | 7 | 3 | 2.4 | 0.2 |
| 7 | 63 | 12 | 20 | 4 | 3.9 | 0.0 | 66 | 15 | 14 | 4 | 3.5 | 0.1 |
| 8 | 69 | 13 | 16 | 1 | 2.4 | 1.2 | 56 | 25 | 9 | 9 | 6.2 | 2.4 |
| 9 | 54 | 15 | 22 | 8 | 7.0 | 0.3 | 47 | 22 | 24 | 6 | 8.5 | 1.5 |
| 10 | 68 | 16 | 11 | 4 | 3.0 | 0.5 | 57 | 27 | 11 | 4 | 4.7 | 0.2 |
| 11 | 61 | 13 | 21 | 4 | 4.3 | 0.0 | 56 | 17 | 22 | 4 | 5.5 | 0.7 |
| 12 | 69 | 18 | 10 | 2 | 2.4 | 0.1 | 60 | 27 | 9 | 3 | 3.6 | 0.2 |
| 13 | 77 | 7 | 14 | 1 | 1.2 | 0.0 | 75 | 9 | 13 | 2 | 1.7 | 0.1 |
| 14 | 57 | 20 | 17 | 5 | 5.6 | 0.1 | 64 | 15 | 16 | 4 | 3.8 | 0.0 |
| 15 | 58 | 14 | 23 | 4 | 4.9 | 0.3 | 69 | 15 | 12 | 3 | 2.7 | 0.0 |
| 16 | 48 | 28 | 13 | 10 | 8.8 | 0.3 | 50 | 36 | 7 | 6 | 5.5 | 0.1 |
| 17 | 57 | 11 | 28 | 3 | 4.4 | 0.7 | 49 | 20 | 23 | 7 | 8.2 | 0.3 |
| 18 | 74 | 6 | 17 | 2 | 1.5 | 0.2 | 69 | 16 | 12 | 2 | 2.5 | 0.2 |
| 19 | 66 | 16 | 15 | 2 | 3.1 | 0.6 | 65 | 18 | 14 | 2 | 3.2 | 0.7 |
| 20 | 74 | 9 | 15 | 1 | 1.6 | 0.3 | 71 | 12 | 13 | 3 | 2.4 | 0.2 |
| Rate 2.0 s | | | | | | | | | | | | |
| 1 | 59 | 23 | 14 | 3 | 4.5 | 0.8 | 44 | 33 | 11 | 11 | 9.8 | 0.4 |
| 2 | 66 | 9 | 18 | 6 | 3.6 | 2.4 | 57 | 18 | 20 | 4 | 5.3 | 0.6 |
| 3 | 69 | 13 | 13 | 4 | 2.9 | 0.6 | 67 | 16 | 12 | 4 | 3.2 | 0.3 |
| 4 | 71 | 14 | 12 | 2 | 2.3 | 0.0 | 51 | 34 | 9 | 5 | 5.5 | 0.1 |
| 5 | 60 | 18 | 17 | 4 | 4.7 | 0.2 | 63 | 21 | 11 | 4 | 3.8 | 0.0 |
| 6 | 68 | 13 | 18 | 0 | 2.4 | 3.3 | 69 | 19 | 10 | 1 | 2.2 | 0.9 |
| 7 | 70 | 14 | 12 | 3 | 2.6 | 0.1 | 69 | 15 | 14 | 1 | 2.4 | 1.2 |
| 8 | 70 | 9 | 18 | 2 | 2.2 | 0.0 | 66 | 13 | 16 | 4 | 3.4 | 0.1 |
| 9 | 64 | 14 | 18 | 3 | 3.6 | 0.2 | 60 | 15 | 17 | 7 | 5.3 | 0.9 |
| 10 | 68 | 21 | 10 | 0 | 2.1 | 3.0 | 62 | 19 | 15 | 3 | 4.0 | 0.4 |
| 11 | 62 | 11 | 22 | 4 | 3.9 | 0.0 | 62 | 8 | 27 | 2 | 2.9 | 0.5 |
| 12 | 56 | 17 | 23 | 3 | 5.3 | 1.6 | 63 | 20 | 11 | 5 | 4.0 | 0.4 |
| 13 | 83 | 4 | 12 | 0 | 0.5 | 0.6 | 77 | 7 | 15 | 0 | 1.1 | 1.3 |
| 14 | 80 | 6 | 11 | 2 | 1.1 | 1.1 | 65 | 12 | 18 | 4 | 3.6 | 0.1 |
| 15 | 69 | 14 | 16 | 0 | 2.3 | 3.1 | 71 | 12 | 14 | 2 | 2.3 | 0.0 |
| 16 | 59 | 22 | 11 | 7 | 5.3 | 1.0 | 52 | 28 | 13 | 6 | 6.5 | 0.1 |
| 17 | 60 | 8 | 27 | 4 | 3.8 | 0.0 | 51 | 20 | 23 | 5 | 7.1 | 1.1 |
| 18 | 72 | 12 | 15 | 0 | 1.8 | 2.4 | 72 | 17 | 9 | 1 | 1.8 | 0.5 |
| 19 | 75 | 11 | 11 | 2 | 1.7 | 0.1 | 71 | 11 | 15 | 2 | 2.2 | 0.0 |
| 20 | 87 | 3 | 8 | 1 | 0.4 | 1.3 | 74 | 12 | 11 | 2 | 1.8 | 0.0 |

No., subject number; $\mathrm{CS1}_{pair}$, RNG trials with or without counting from the previous to the present trial; $\mathrm{MIR}_{pair}$, RMG trials with or without mirroring from the previous to the present trial. After Bonferroni correction for multiple comparisons, none of the associations is significant predominant form of bias, whereas for motor RMG, bias related to the spatial relations of hands or fingers is more relevant.[1] Effects of rate and dual task performance are always strongest for the predominant type of bias in each modality. The different set sizes in the verbal and motor tasks (9 numbers vs. 8 fingers) explain just minor deviations from equal effect size, as shown by previous studies applying the same set size for both tasks (Baddeley et al. 1998; Towse 1998).

### Dual task costs of performance quality

An established paradigm to examine dual task interference tests subjects on two reaction time tasks in rapid succession (Pashler 1994; Lien et al. 2005; Dux et al. 2006). Each task has a separate stimulus (S1 vs. S2) and requires a specific response (R1 vs. R2). When the two tasks are separated by a long interval, performance in the second task is not affected by the execution of the first task. However, as the onset asynchrony between S1 and S2 is reduced and the two tasks overlap, reaction times in the second task slow down. This slowing (also known as the psychological refractory period) is commonly used to measure the magnitude of dual task interaction (Welford 1952; Pashler 1994). In contrast, subjects in our paradigm had a constant predefined timeframe to produce responses in the single and dual task conditions. Because our paradigm does not allow subjects to spend extra time for response selection in the more difficult dual task condition, the higher demands of the dual condition are reflected in a drop of performance quality instead of prolonged reaction/completion times.

A relevant feature of our study was that our participants' strategies were not predetermined with respect to the temporal order in which the two components of the dual task condition were executed, neither by explicit instructions nor by any methodological feature such as the temporal relation between a main versus subsidiary task. Subjects in our experiment could choose freely on every trial the temporal order by which they executed the two tasks. In addition, unlike some dual task studies combining two reaction time tasks (e.g., Dux et al. 2006), our analysis was not restricted to a proportion of trials executed in a particular temporal order. We, therefore, think that our results can supplement other dual task experiments where the participants' chosen strategies were influenced by explicit or implicit task constraints.

### Effects of task load

Dual task costs in sequential reaction time tasks are virtually eliminated when at least one of the two tasks is very simple and has the property of so-called 'ideomotor compatibility' (Greenwald and Shulman 1973; Lien et al. 2005). For the interpretation of our results, it is, therefore, important that both random generation tasks were demanding. In the following paragraphs, we discuss our results in the context of other experimental paradigms, refer to alternative concepts of working memory, and eventually demonstrate that both RNG and RMG are demanding tasks.

The shadowing task is an auditory-verbal test in which participants repeat what they hear (e.g., say "A" or "B" in response to the spoken letter "A" or "B", respectively). If this task is executed together with a more demanding task, performance of the secondary task is not diminished. It was proposed that because of its striking simplicity shadowing does not require any of the operations carried out by the central executive (e.g., focusing of attention, response selection, modification of production strategies) and can therefore bypass the central bottleneck (Greenwald and Shulman 1973; Lien et al. 2005). Subsequent studies have refined the 'bottleneck theory' and suggested different models depending on whether this effect is partial or complete, occurs in all or just some trials, and requires one or two ideomotor-compatible tasks (Lien et al. 2005).

On the same line of arguments, Lavie et al. (2004) proposed that interference in dual task processing is absent if one task is much easier than the other because the relevant information of the easier task is not perceived when there is insufficient capacity. This might be mediated by a passive perceptual selection mechanism that allows for the suppression of information in situations of overload. In Lavie et al.'s original conceptualization, the focus was on the perception of sensory stimuli for the simpler of the two dual task components (e.g., visual stimulus in a reaction time task which is used as the simpler task in a dual task experiment), but in the case of random generation tasks this could be adapted to introspective perception of performance feedback (self-monitoring). Here, in contrast to bottleneck theories, it is the balance of task demands rather than the absolute demands of either task which is essential for the predicted effect.

However, there is ample evidence that in our study both RNG and RMG were demanding. The analysis of standard measures of randomness showed that performance quality in both random generation tasks deteriorated under dual task compared to single task conditions. For example, in RNG, the magnitude of the most relevant CS1 bias increased from $z$ score 2 to $z$ score 4 (Fig. 2). This increment would not occur if the secondary task (RMG, in this

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[1] Motor mirroring involves a change of hands and, therefore, a shift of the predominating contralateral movement-related activation to the other hemisphere (Dirnberger et al. 2002) whereas verbal mirroring occurs in reference to an abstract number and is not associated with a similar shift of lateralized activation. It is therefore not clear how similar the brain mechanisms suppressing motor and verbal mirroring are.

case) was rather simple, because simple tasks would not occupy resources which would then be lacking for the performance of the other task. In addition, neuroimaging studies in healthy subjects found a similar network of cortical fronto-parietal and subcortical activation during verbal and motor random generation tasks (Jahanshahi et al. 2000; Deiber et al. 1991), and neurological patients with dysfunction of this network are impaired in both motor and verbal random generation (Annoni and Pegna 1997; Brown et al. 1998; Robertson et al. 1996; Spatt and Goldenberg 1993). Finally, according to subjective reports, our participants considered both RNG and RMG as demanding.

### Dual task costs are not due to task alternation

Our results show that for the dual task condition, transient increase of bias in one random generation task was not associated with a concurrent decrease of bias in the other random generation task. This indicates that resources of the central executive are not re-allocated from one to the other task, and consequently there is no gaining and fading of some coupled supervisory functions. At a behavioral level, as subjects do not focus on one or the other task in an alternating fashion there is no parallel up versus down of performance in the two tasks.

Our analysis of alternation was restricted to those types of bias which can be tested from one trial to the next. It is still possible that alternation occurs for the suppression of some other form of bias, e.g., correction of uneven distribution of responses. Distribution of alternative responses is tested via chi-squared statistics which cannot be applied meaningfully to subsequences shorter than double the set size. For a set size of eight (RMG) or nine (RNG) items as in the present study, such subsequences are longer than the likely duration between two alternations. However, possible effects of alternation on response selection in dual task random generation tasks could be tested in future studies using a similar design with a smaller set size.

Our analysis would also fail to detect effects of alternation if it only occurs for very short time intervals which could not be analyzed with our methodology. However, we consider it unlikely that a conscious process as alternation could occur for time intervals shorter than the duration of the so-called ‘specious present’ (Durgin and Sternberg 2002).

### Concurrent response selection and the central bottleneck

If alternation is not responsible for the reduced performance in the dual task condition, how else can the dual task results be explained? In the dual task condition, there is the demand of response selection for the two tasks which needs to be completed within the time constraint of the pacing stimulus. The necessity of such active response selection from a set of alternative responses, numbers 1–9 for RNG and fingers 1–8 for RMG, for the two tasks concurrently would involve the central executive. Studies with the psychological refractory period paradigm have revealed that the response time to a second task becomes longer as the stimulus onset asynchrony between the two tasks decreases (Welford 1952). On the basis of this finding, it has been argued that dual task costs are due to a ‘central bottleneck’ in information processing which interferes with two response selection operations being completed concurrently (Pashler 1994).

For all random generation tasks, responses have to be selected out of a pool of possible alternatives within a certain time limit set by the pacing stimulus. The need to synchronize responses with the pacing stimulus is an additional demand which can impose a time pressure on selection of a response on each trial. According to this bottleneck theory, in the dual task condition parallel response selection for the two tasks is not possible. Consequent to such serial processing, queuing of response selection must occur: for the random generation tasks of our study, either one response (RNG or RMG) is retrieved first, and the other one thereafter. The behavioral consequence for both tasks is a reduction in the quality of randomness similar to the effects of faster rate on performance. At faster rates and under dual task conditions, since participants have less time for response selection, the quality of their random generation performance deteriorates and their output is less random. The costs of dual task performance and faster rates are identical and mediated by the demands of response selection under conflict. In the dual task condition, because queuing is present in each and every trial, there are no subsequences with better quality of randomness in one task at the expense of the other task. The quality of randomness of the output is reduced in both tasks and for the entire time of dual task performance.

The results of Baddeley et al. (1998) can be explained by similar processes. In their study, quality of randomness in a RMG task was affected more severely by concurrent performance of a word fluency test than by concurrent performance of a RNG task. This result was attributed to the higher demands of ‘switching’ in the word fluency task. An alternative explanation would be that response selection and word retrieval in the word fluency task is more demanding than in RNG, because fluency has stricter criteria about which items are correct. The list of numbers available for selection in the RNG task is much smaller (10 numbers in the study by Baddeley et al.) than the list of possible words in the letter word fluency task (more than 10,000). The larger repertoire of responses in the fluency task combined with the instruction that words must not be repeated makes this task more difficult. For RNG, in contrast, set size is smaller than the number of items to be generated so it is clear that every number can be said more than once. Response selection/word retrieval and monitoring are therefore more difficult in word fluency than RNG.

### Capacity sharing and alternative concepts of central executive functions

Tombu and Jolicœur (2003) questioned the assumption that the central executive has fixed capacity. According to their reasoning, human subjects increase their efforts when confronted with a more demanding dual task compared to the easier single task situation, and according to some experimental results may actually succeed to boost their performance (Schumacher et al. 2001). This could be achieved by either increasing the available capacity of the central executive or via better utilization of the existing capacity, which may be subject to task-related and motivational factors. Our results can neither support nor reject the possibility that human subjects can increase the capacity of the central executive under the high demands of dual task performance.

According to an alternative hypothesis, the capacity of the central executive is not permanently increased for both tasks but can be switched between task instantaneously and without costs (Tombu and Jolicœur 2003). Such a model would meet the same criteria as the central capacity sharing model. However, modeling showed that the rate of switching had to be in the sub-second range to achieve relevant gains in performance (Miller and Bonnel 1994). This appears implausible in light of the limitations of other neuropsychological abilities. Our results do not support the hypothesis of rapid switching insofar as we found no indication of switching down to the 500 ms range, a rate for which switching at least appears conceivable.

### Response selection in the context of the network modulation model of RNG

Using neuroimaging and rapid rate transcranial magnetic stimulation (rTMS), we have previously demonstrated that the dorsolateral prefrontal cortex (DLPFC), particularly in the left hemisphere, is engaged in paced RNG and plays an essential role in inhibition of habitual counting (Jahanshahi and Frith 1998; Jahanshahi et al. 2000). The DLPFC is also relevant for response selection in a task without a working memory component (e.g., Hadland et al. 2001). It is, therefore, likely that performance of the RNG and RMG task engages this area of the prefrontal cortex, with additional engagement of other brain areas such as the precuneus which has been previously shown to be specifically activated during dual task performance (Wu and Hallett 2008). Others have suggested that the inferior frontal gyrus plays a role in dual task processing in relation to coordination of temporal order (Szameitat et al. 2002) and cognitive processes necessary for the concurrent mapping of sensory information onto motor responses (Stelzel et al. 2006). The neural correlates of concurrent performance of RNG and RMG remain to be clarified.

In future studies, we propose to use rTMS and analysis of transient bias to investigate the neural correlates and underlying mechanisms of dual task costs when healthy controls perform RNG and RMG concurrently to provide further support for our proposal that response selection is the key process contributing to dual task interference effects.

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