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# Brain potentials index executive functions during random number generation

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## Abstract

The generation of random sequences is considered to tax different executive functions. To explore the involvement of these functions further, brain potentials were recorded in 16 healthy young adults while either engaging in random number generation (RNG) by pressing the number keys on a computer keyboard in a random sequence or in ordered number generation (ONG) necessitating key presses in the canonical order. Key presses were paced by an external auditory stimulus to yield either fast (1 press/800 ms) or slow (1 press/1300 ms) sequences in separate runs. Attentional demands of random and ordered tasks were assessed by the introduction of a secondary task (key-press to a target tone). The P3 amplitude to the target tone of this secondary task was reduced during RNG, reflecting the greater consumption of attentional resources during RNG. Moreover, RNG led to a left frontal negativity peaking 140 ms after the onset of the pacing stimulus, whenever the subjects produced a true random response. This negativity could be attributed to the left dorsolateral prefrontal cortex and was absent when numbers were repeated. This negativity was interpreted as an index for the inhibition of habitual responses. Finally, in response locked ERPs a negative component was apparent peaking about 50 ms after the key-press that was more prominent during RNG. Source localization suggested a medial frontal source. This effect was tentatively interpreted as a reflection of the greater monitoring demands during random sequence generation.

*Keywords:* Random number generation; Event-related brain potentials; Executive functions; Inhibition; Error-related negativity; Source localization; Frontal cortex

## 1. Introduction

To steer, orchestrate, and monitor the human cognitive apparatus, a set of metacognitive functions is necessary. These executive functions have multiple facets (Baddeley, 1996, Baddeley, 1998; Shallice and Burgess, 1996) and, depending on the individual framework, have been divided into two (Carter, 2001) to five (Smith and Jonides, 1999) different groups of mechanisms. A major division can be made between strategic aspects of cognitive control, involving top-down control, goal representation and attention allocation on the one hand and evaluative processes or performance monitoring functions on the other hand. One paradigm that targets aspects of cognitive control is the generation of random sequences. First reports using this paradigm date back to the 1950s (e.g. Mittenecker, 1958). In its typical incarnation, this task requires the generation of numbers in a random order, whereby the speed of the production is paced by an external stimulus (Baddeley et al., 1998).

Recent studies have suggested that difficulties in random number generation (RNG) are not attributable to a misconception of randomness (Baddeley, 1998; Tune, 1964; Wagenaar, 1970) or a consequence of short term memory problems, as it has been postulated earlier (Baddeley, 1966; Tune, 1964; Wagenaar, 1970; Brugger, 1997; Towse and Valentine, 1997). Rather, using dual-task paradigms it has been shown that subjects need the ability to inhibit prepotent responses (Towse and Valentine, 1997). More

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specifically, Baddeley et al. (1998) pointed out that inhibition and switching of retrieval plans are crucial components of random generation.

The frontal lobes have been shown to play a prominent role in RNG on the basis of lesion studies (Spatt and Goldenberg, 1993). A PET study in young healthy subjects (Jahanshahi et al., 2000) contrasting RNG and counting revealed activation in distributed cortical areas, which led Jahanshahi and co-workers to propose the “network modulation model”. This model holds that inhibition of habitual sequences during RNG is related to the dorsolateral prefrontal cortex (DLPFC). This view is supported by the fact that transcranial magnetic stimulation (TMS) over the left DLPFC significantly decreases randomness (Jahanshahi et al., 1998; Jahanshahi and Dirnberger, 1999).

Thus, previous behavioral and imaging studies of RNG have focused on strategic and inhibitory functions. Surprisingly, little is known about evaluative and monitoring functions that are without doubt required by RNG.

The present searched for electrophysiological correlates of both, strategic and monitoring functions, during RNG using event-related brain potentials (ERP). ERPs are minute task-related voltage fluctuations which can be measured non-invasively with electrodes located on the scalp. Although ERPs are somewhat limited in spatial resolution they have the advantage of a very high temporal resolution (Münte et al., 2000).

The traditional RNG paradigm was modified in the present investigation by introducing a dual task manipulation: The primary task contrasted a conventional RNG condition with an ordered number generation (ONG) task, which required subjects to generate a schematic sequence of numbers in a count sequence (i.e. 1, 2, 3... etc). The use of identical auditory stimuli that were used to pace the number production in both tasks allowed to assess the effects of random versus ordered behavior by comparing the wave form characteristics for the two conditions.

In addition, the secondary task comprised a traditional oddball-paradigm, which required to press a target key, whenever a specified rare target tone appeared instead of the pacing stimulus of the primary task. This manipulation was introduced to monitor the differential demand of cognitive resources by the two conditions of the primary task (Hoffman et al., 1985; Isreal et al., 1980). We hypothesized that RNG would be more attention-demanding than ONG and thus expected the P3b component to the oddball-targets to be smaller during RNG.

## 2. Method

### 2.1. Subjects

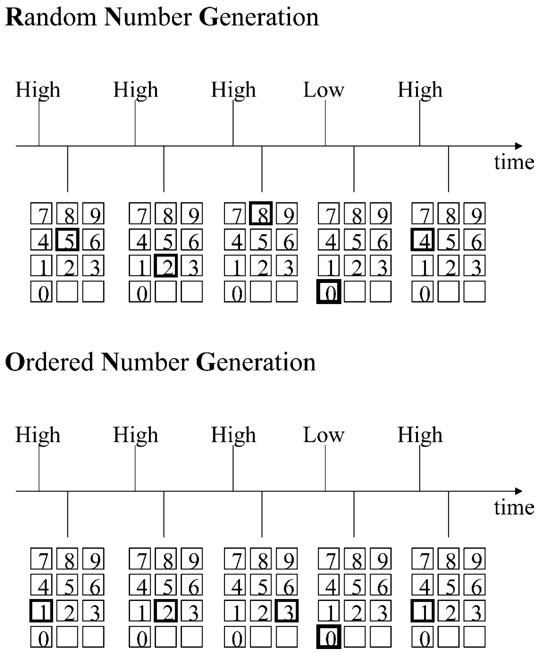
Sixteen volunteers (nine women of age 24–41 years, mean 31.6 years) served as subjects. All participants were right handed, well educated (mean 19.4 years of education, S.D. = 1.75 years), and had no history of neurological disorders.

### 2.2. Stimuli and procedure

The subjects sat in a comfortable chair and had a keyboard in front of them which contained the keys 0–9 of the number block and the space bar. All other keys had been removed. A loudspeaker was positioned 1 m in front of the subjects and was adjusted such that sounds had a volume of 91.5 dB [SPL]. During each run 125 frequent standard sounds (635 Hz) and 18 target sounds (435 Hz) were presented in random order.

The primary task (number generation) comprised two conditions. The first condition (ordered number generation, ONG) required the subjects to press the number keys in the canonical order, i.e. 1–9. They had to press the selected key as fast as possible, whenever a standard tone was presented. Whenever an infrequent “target” tone was presented, the subjects had to press the “0”-key (secondary oddball task). After such a target stimulus the subjects had to start again with ONG commencing with the number “1”.

For the second condition (random number generation, RNG) the subjects were instructed to press the keys 1–9 in a randomised order in response to the frequent standard tones. Again, the lower target tones required to press the “0” key. An illustration of the task is found in Fig. 1. The concept of randomness was explained emphasizing that occasional repetition of numbers is a part of real randomness. In addition, randomness was explained with the “hat” analogy (Horne et al., 1982) as also used in other studies (Baddeley et al., 1998; Jahanshahi et al., 1998; Jahanshahi and Dirnberger, 1999). Subjects were told that “As an


**R**andom **N**umber **G**eneration

**O**rdered **N**umber **G**eneration

Fig. 1. Illustration of the task.

example of the concept of randomness, suppose we had written the numbers 1–9 on pieces of paper and put them into a hat. You take out one piece of paper, call out the number on it and return it to the hat. Then you would reach for another piece of paper and do the same thing. The series of numbers you would call out in that way would be random". Both conditions, RNG and ONG, had to be performed with two different speeds (slow versus fast) and, on separate runs, with the right and the left hand. Each run comprised 125 standard and 18 target stimuli. The interstimulus interval (ISI), i.e. the time between the offset of one auditory stimulus and the next, was 1300 ± 150 ms the "slow" presentation mode and 800 ± 100 ms the "fast" presentation mode. In total the subjects were tested in eight different experimental conditions, each of which was administered twice. The order of the 16 runs was counterbalanced across 16 subjects.

The subjects were instructed to use their index finger only.

### 2.3. Data recording

The electroencephalogram was recorded using tin electrodes mounted in an electrode cap (Electro-Cap International) from the international 10–20 electrode positions (Jaspers, 2001) and the additional electrode positions FC3, FC4, FT7, FT8, CP3, CP4, TP7, TP8, FCz, and CPz. Electrode impedances were maintained below 10 kΩ. The EEG was amplified with a bandpass of 0.5–50 Hz and digitized at a rate of 250 samples/second. All scalp electrodes were referenced to an electrode located on the right mastoid. Ocular fixation was verified by recordings of the horizontal EOG. Trials contaminated by eye blinks were detected by vertical electrooculogram and rejected by a computer routine. For each subject amplitude criteria for the rejection of blinks were determined individually. ERPs were obtained by averaging time-locked to the tone-stimuli or to the motor responses. Different averages were computed as a function of the specific response sequences. Wave forms were quantified by mean amplitude measures which were subjected to analysis of variance.

Neural generators of the brain activity were estimated by computing the cortical three-dimensional distribution of current density using the LORETA (low resolution brain electromagnetic tomography) algorithm (Pascual-Marqui et al., 1994) which solves the inverse problem by assuming related orientations and strengths of neighboring neuronal sources without assuming a specific number of generating sources. The "smoothest" of all possible activity distributions is thereby obtained. The version of LORETA employed here (Pizzagalli et al., 2002) uses a three-shell spherical head model registered to standardized stereotactic space (Talairach and Tournoux, 1988) and projected onto the Montreal Neurological Institute standard average brain. Computations were restricted to cortical gray matter and hippocampi (spatial resolution of 7 mm, 2394 voxels) as described elsewhere (Pizzagalli et al., 2002).

To assess behavioural performance reaction times, error rates for the targets, and the stream of numbers were recorded.

### 2.4. Measurement of randomness

According to Ginsburg and Karpiuk (1994) there are three important factors in the description of randomness: cycling, repetition and seriation. For the present study, we selected four different measurements: The number of immediate repetitions of the same digit was calculated to yield the parameter REP (Ginsburg and Karpiuk, 1994).

Cycling refers to the distance of successive occurrences of the same digit, and was measured by the GAP Score (Ginsburg and Karpiuk, 1994). This score results from calculating the median of the gap between successive occurrence of the 1's, the 2's etc.

Seriation refers to the tendency to generate during RNG sequences with the canonical order of the numbers (e.g. 2–4). To describe seriation the occurrence of steps of one (e.g. 2–3, CS1) and steps of two (e.g. 2–4 CS2) as described by Spatt and Goldenberg (1993) was counted. These measures take into account the length of the series. The sequence length was squared to give greater weights to longer sequences. An increase of the measure CS1 would indicate less randomness.

## 3. Results

### 3.1. Indices of randomness

An increase in CS1 in the "fast" mode indicates the expected decrease in randomness ($T = -2.8$, df = 15, $P = 0.008$, one-tailed) with increasing speed of the task (Table 1). Complementary to CS1, CS2 decreased significantly ($T = 1.8$, df = 15, $P = 0.048$, one-tailed). The GAP score ($T = 0.8$, df = 15, n.s.) and the REP score ($T = 1.4$, df = 15, $P = 0.093$, one-tailed) did not change significantly.

### 3.2. Reaction times and error rates

Response times for non-targets were shorter during ONG (Table 2; $F(1, 15) = 30.1$, $P < 0.001$). There also was

Table 1
Behavioral indices of randomness

| | Low speed | | High speed | |
|---|---|---|---|---|
| | Mean | S.D. | Mean | S.D. |
| CS1 | 37.42 | 8.90 | 42.08 | 14.24 |
| CS2 | 28.40 | 4.46 | 25.89 | 6.68 |
| GAP | 7.81 | 0.56 | 7.71 | 0.58 |
| REP | 4.77 | 3.13 | 4.16 | 2.37 |

*Note:* CS1 is the count score 1, CS2 the count score 2, GAP the median of the gap between occurrences of the 1's, 2's etc. and REP the mean number of repetitions.

Table 2
Reaction times and error rates

| | Low speed RT (ms) (S.D.) | ERR (%) S.D. | High speed RT (ms) S.D. | ERR (%) (S.D.) |
|---|---|---|---|---|
| ONG–target | 556 (51) | 0.9 1.3 | 518 (46) | 1.4 (1.6) |
| RNG–target | 579 (58) | 1.3 1.2 | 526 (45 | 1.9 (1.6) |
| ONG–standard | 361 (74) | | 355 (58) | |
| RNG–standard | 417 (66) | | 388 (55) | |

*Note:* The data at the top refer to the reaction times to the targets (secondary oddball task), the data in the lower half of the table to the button press latencies in the primary RNG/ONG task. ONG is the ordered number generation, RNG the random number generation, and ERR the mean error rate.

an effect of speed, as response times were shorter in the fast mode ($F(1, 15) = 8.8$, $P < 0.01$). In addition, a significant speed by task interaction was obtained reflecting the fact that fast/slow response time differences were more pronounced in the RNG condition ($F(1, 15) = 7.1$, $P = 0.018$). Subjects committed more errors in the RNG condition ($F(1, 15) = 15.3$, $P = 0.001$) but there was no effect of speed ($F(1, 15) = 0.8$, n.s.) or the speed by condition interaction ($F(1, 15) = 0$). There was no effect of response hand ($F(1, 15) = 1.2$, n.s.).

Reaction times for targets were shorter during the ONG condition than during RNG (Table 2, $F(1, 15) = 5.4$, $P = 0.034$). Moreover, reaction times were generally shorter during the fast mode ($F(1, 15) = 60.1$, $P < 0.001$). The speed by condition interaction just failed to reach the significance level ($F(1, 15) = 4.3$, $P = 0.056$). Subjects committed more errors in the fast mode ($F(1, 15) = 10.0$, $P = 0.006$) and in the RNG condition ($F(1, 15) = 6.2$, $P = 0.025$). There was no speed by condition interaction for error rates ($F(1, 15) = 0.1$). No effect of response hand was observed ($F(1, 15) = 0.96$, n.s.).

### 3.3. P3b Component to target stimuli

The P3 component to the target stimuli can be derived from Fig. 1. Its amplitude, quantified by a mean amplitude measure (time-window 300–500 ms) was larger in the slow presentation mode ($F(1, 15) = 61.8$, $P < 0.001$). Also, the ONG condition resulted in higher P3 amplitudes than the RNG condition ($F(1, 15) = 13.2$, $P < 0.002$). Although the ONG/RNG difference appeared to be more pronounced for the slow presentation mode, no interaction between the factors speed and condition was found ($F(1, 15) = 1.5$, n.s.).

### 3.4. Stimulus-locked responses to standards during RNG

Stimulus-locked responses to standard events during RNG were calculated separately for (1) standard tones followed by a repetition response (i.e. the subject pressed the same key as in the immediately preceding trial), and (2) standard tones followed by a "random" response (e.g. "8" after "5") . The resulting ERPs are presented in Fig. 2 for the slow presentation rate. These were quantified by a mean amplitude measure in a time window from 120–180 ms at the electrode FCz. An ANOVA with two factors (speed and repetition/random) revealed an effect for the factor speed ($F(1, 15) = 8.78$, $P < 0.01$) and ONG/RNG ($F(1, 15) = 9.04$, $P = 0.009$). There was no effect of interaction ($F(1, 15) = 0.725$, $P = 0.41$).While ERPs for the fast mode did not show a differential response for the two ERP categories outlined above ($F(1, 15) = 0.54$, $P = 0.47$), the wave forms obtained in the slow presentation mode did ($F(1, 15) = 10.5$, $P =$

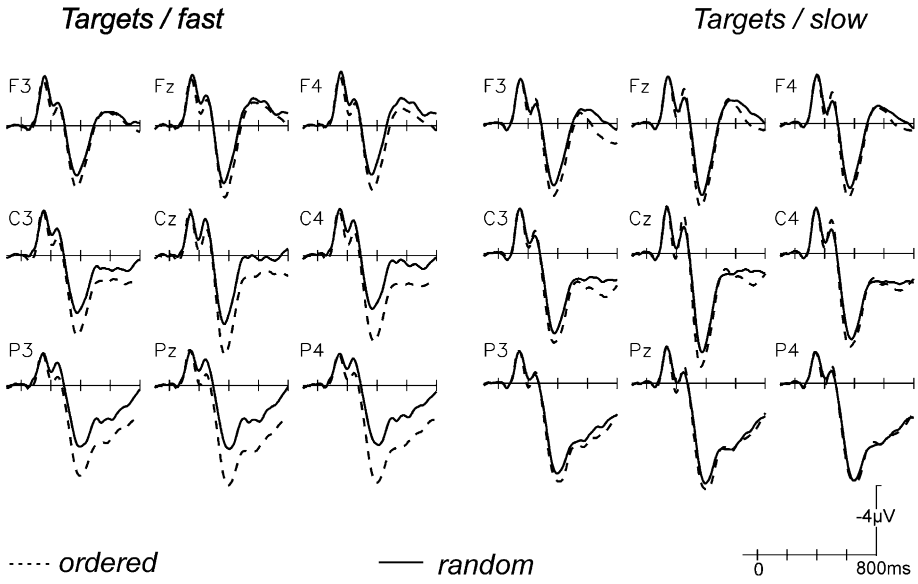


Fig. 2. Grand average ERPs to target stimuli (secondary task). Target ERPs are characterized by prominent P3 component, which is more pronounced for the ordered number generation task, especially in the fast condition.

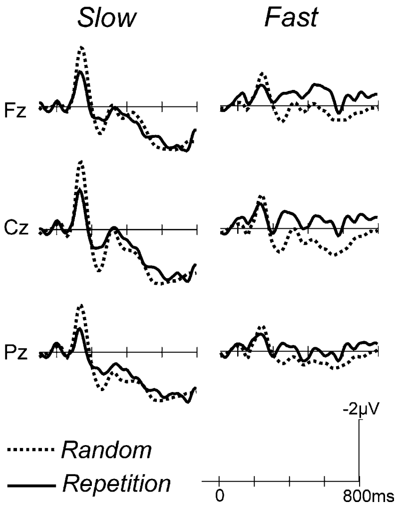


Fig. 3. Grand average ERPs time-locked to standard tone stimuli from the random number generation condition. Those tones that were associated with random behavior (e.g. eight after five) gave rise to greater negativity than tones that were followed by a repetition response. This effect was more pronounced at the slower presentation rate (left column) than at the faster rate (right).

0.005). The scalp distributions of the negative peaks (mean amplitude 120–180 ms) are shown in Fig. 3. Interestingly, a grossly different scalp topography can be observed for the different ERP categories. While for the negativity to standards followed by repetitions showed a fronto-central mid-line distribution typically seen for the auditory N1 component, the standards followed by “random” responses were associated with a maximum negativity over the left frontal region.

This effect was followed up by estimation of the neural generators using the LORETA approach (Fig. 3). This analysis suggests that the left frontal effect for the trials that elicited random behavior is generated by left dorsolateral prefrontal cortex (co-ordinates $X = -45$, $Y = 6$, and $z = 38$, Brodmann area 9, Inferior Frontal Gyrus; additional source at $X = -45$, $Y = -74$, and $Z = 8$, Brodmann area 39, Middle Temporal Gyrus). No such activity was observed for the repetition trials.

### 3.5. Response-locked averages

Response-locked averages were computed time-locked to the button-presses to standard stimuli in the ONG and RNG condition, i.e. to the critical motor responses in the primary task. This analysis was done to evaluate whether or not brain wave activity reminiscent of the so-called Error related Negativity (“ERN” or “Ne”) could be detected. In particular, it was of interest, whether responses during RNG are associated with a greater ERN component, assuming that these trials would lead to an increased response conflict. ERPs were averaged for epochs covering the time-interval −400–400 ms with the button press occurring at time 0. The time-period −100–0 ms was used as a baseline. As suggested by Luu and Tucker (2001) EEG was digitally filtered with a 4–12 Hz digital band-pass filter (half amplitude cut-off) in order to remove the slow waves for the computation of the ERNs. A small negative peak with a frontocentral distribution and a latency typical for the ERN was observed (see Fig. 5) and quantified by a mean amplitude measure 0–75 ms. The mean amplitude of this component was slightly larger for the slow presentation rate. An ANOVA with three factor speed versus ONG/RNG versus Electrodes [Fz, Cz, FC3, and FC4] revealed a significant interaction of electrodes and ONG/RNG ($F(3, 45) = 6.3$, $P < 0.001$).

Source localization suggested a medial frontal source in the supplementary motor area (SMA) and possibly extending to the cingulate gyrus (peak coordinates: $X = -3$, $Y = -11$, and $Z = 64$; Brodmann area 6, Medial Frontal Gyrus).

### 3.6. Lateralized readiness potentials (LRPs)

Response locked lateralized readiness potentials (LRPs) were computed for the time window from −700 to 1200 ms using the double subtraction procedure(Coles, 1989; de Jong et al., 1988). However, typical but very low-amplitude LRP waveforms were obtained in four subjects only. Thus, LRPs were not analyzed further. We believe that this is due to the following facts: First, the rate of finger movements (for the button press) was considerably higher than that used in the typical self-paced readiness potential paradigms. Second, within a given run, subjects only used one hand, thus the motor cortex of the subjects might have been saturated.

## 4. Discussion

To our knowledge the present study is the first to use the ERP method to investigate effects of random number generation. In the following discussion we therefore try to interpret the result pattern by relating the current findings to results from different paradigms probing executive functions. As a modification of the standard paradigm (e.g. Baddeley, 1966; Jahanshahi et al., 2000) the present experiment employed the dual task methodology (Hoffman et al., 1985; Isreal et al., 1980) with the aim to test the attentional resources of RNG: Thus, the primary task was to produce numbers in either an ordered (ONG) or a random (RNG) sequence, while the secondary task was to respond by a specified key-press whenever a rare target tone occurred.

### 4.1. Attentional demands

Reaction times to target and standard stimuli were somewhat longer and error rates were higher during the RNG task suggesting that the RNG task is more demanding than ONG. The current data are therefore in line with a number of behavioural studies (Baddeley, 1966; Robertson et al., 1996). This is further corroborated by the ERP pattern to the target stimuli. As in other dual task studies conducted with ERPs (Kramer et al., 1983, 1987; Isreal et al., 1980), the amplitude of the P3b component to the targets in the secondary oddball task can serve as an indirect measure of processing demands of the primary ONG/RNG task (Kok, 2001). As the physical stimuli were identical for the RNG and ONG conditions, the reduced amplitude of the P3b during RNG suggests that more processing resources are taken up by this condition. Following Baddeley et al. (1998) the reduced P3b in the secondary task likely reflects the greater need of guided activation in the RNG condition, thus leaving only limited resources for the secondary task.

### 4.2. *Speed and random number generation*

As expected, there was a significant effect of speed on the quality of RNG. In the fast mode subjects were more inclined to count in ones (CS1 measure). At the same time the CS2 measure declined. This replicates earlier results of Jahanshahi et al. (1998) and Baddeley (1966) and has been interpreted as a result of the limited capacity of executive functions. However, the scores GAP and REP did not change. This was not expected as they usually change as a function of the degree of randomness. In contrast to most studies, however, the subjects in the present experiment were explicitly instructed that repetition is a feature of a random sequence as suggested by Schmuck and Wöbken-Blachnick (1996). It is thus possible that the instruction primed the subjects to produce repetitions, leading to an unchanged REP score. The unchanged GAP score likely is attributable to the introduction of target tones necessary for the secondary task. The interruptions brought about by the target stimuli might have counteracted the tendency to cycle through the nine numbers. We therefore rely primarily on CS1 and CS2 to judge randomness.

Note, that in a previous PET study (Jahanshahi et al., 2000) marked differences of task-related activation of DLPFC were found between presentation at intervals of 0.5 and 1.5 s. The authors therefore concluded that a 0.5 s might be too fast to keep up random behavior and that the DLFPC can not control or select correctly the responses under these conditions, thus favouring habitual, counting behavior. One might therefore argue that presentation at intervals of 0.7–0.9 and 1.150–1.450 s as in the current study precluded our finding of greater differences in random behavior between the two intervals. As the CS1 index was indeed different between the two intervals, we do not believe this to be the case, however.

### 4.3. *Executive functions and random behavior*

Several taxonomic systems for executive functions exist, with one current system distinguishing between strategic and evaluative functions (Carter, 2001). Anatomically these functions are thought to be supported by different structures based on lesion and neuroimaging evidence. The dorsolateral prefrontal cortex is the core structure for strategic aspects of behavior (Miller, 2000; Miller and Cohen, 2001). The anterior cingulate cortex (ACC) (Cohen et al., 2000; Gehring and Fencsik, 2001; Luu and Tucker, 2001; MacDonald et al., 2000) and the adjacent supplementary motor area (SMA) (Ullsperger and von Cramon, 2001; Garavan et al., 2002) on the other hand are assumed to support evaluative and monitoring functions .

A key element in RNG is the need to compare past and present behavior in order to assure randomness. Therefore, monitoring functions should be called upon by random number generation more so than by simple ordered number generation. With regard to monitoring, the ERPs time-locked to the response are of interest. Here, a larger amplitude for the peak immediately following the response was found for the RNG task. While the overall amplitude of this effect is quite small, the fact that it can be traced to a medial frontal generator (see Fig. 4) suggests that this might be an instance of the ERN. This brain potential component has been interpreted as a reflection or response conflict (Gehring and Fencsik, 2001; Cohen et al., 2000; Luu et al., 2000; Luu and Tucker, 2001; Van Veen and Carter, 2002). While in the ONG task the order of responses is completely determined, this is not the case in RNG. Rather, the subject has to decide between a number of response alternatives, some of which being more compatible with random behavior than others.

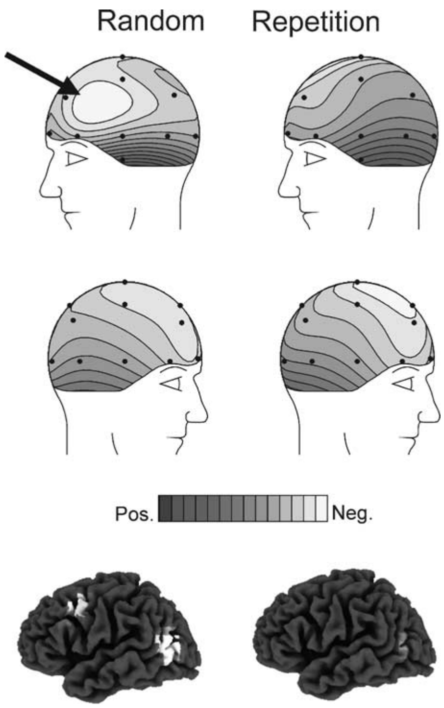


Fig. 4. (Top two rows) Spline interpolated isovoltage maps (mean amplitude 120–160 ms) for standard stimuli from the RNG task. Clearly, a left frontal maximum is obtained for those trials associated with random behavior, while no such left frontal negativity could be demonstrated in trials with repetitive behavior. (Bottom row) Source image obtained with the LORETA algorithm. The white zones indicate current densities above $2\times10^{-3}$ $\mu$A/mm$^2$.

Theories of random number generation emphasize the need for inhibition of habitual sequences (Baddeley et al., 1998; Jahanshahi et al., 1998; Jahanshahi and Dirnberger, 1999). The comparison of ERPs to standard stimuli in the RNG task that were associated with stimulus repetition and with those to standard stimuli associated with "random" behavior, revealed that only the latter were associated with a left frontal ERP effect. This could be attributed to the left dorsolateral prefrontal cortex (Brodmann area 9, Figs. 2 and 3). Interestingly, this area has also been found in a recent PET study investigating RNG (Jahanshahi et al., 2000). In this study the left BA 9 emerged in the subtraction RNG minus COUNT and was associated with lower "counting in ones" and higher "counting in twos" behavior. This led the authors to propose that this brain area is associated with the suppression of habitual counting. The same interpretation might also hold for the effect observed in the present study. In this respect, it is worthwhile that a number of studies have described a specific ERP component in the so-called go/no-go paradigm. Whenever an individual is asked to respond to one class of stimuli (go trials) and to withhold responses to another class of stimuli (no-go trials), the ERP on no-go (relative to go) trials is characterized by a large negativity (1–4 μV) between 100 and 300 ms after stimulus onset (N200), especially over fronto-central sites (Simson et al., 1977; Sasaki et al., 1993; Thorpe et al., 1996). The amplitude of the N200 is assumed to be a function of neuronal activity required for ''response inhibition" (Gemba and Sasaki, 1989, 1990; Jodo and Kayama, 1992). However, when the scalp distribution of the go/no-go N200 has been inspected, mostly a maximum at mid-frontal or right-frontal locations has been obtained (e.g. Rodriguez-Fornells et al., 2002; Schmitt et al., 2001). We therefore believe that the current left-frontal effect is different from the standard go/no-go ERP (Fig. 5).

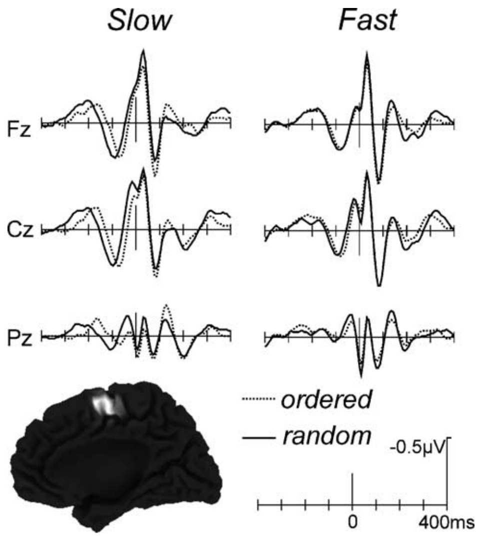


Fig. 5. ERPs time-locked to the motor response (band-pass 4–12 Hz). A negative peak followed immediately after the response, which had a fronto-central mid-line maximum and was more pronounced in the random number generation task. The source analysis suggested a medial frontal source (lower left). The white zones indicate current densities above $2 \times 10^{-3}$ μA/mm$^2$.

It might also be interesting to relate the left frontal effect to the central executive that in Baddeley's influential working memory model supervises behaviour in demanding tasks such as RNG (Baddeley, 1986). However, a number of recent brain imaging studies have failed to pinpoint candidate brain regions that could be viewed as the site of the central executive (Gruber and von Cramon, 2003; Bunge et al., 2000; Bunge et al., 2001).

### 4.4. *Conclusions*

The present data set attests to the utility of electrophysiological measures to reveal the engagement of different portions of the frontal cortex in the generation of random sequences. The data suggest that RNG in comparison to ONG draws more heavily on attentional resources (P3 modulation in the target ERPs), that RNG requires monitoring functions (modulation of the ERN-like component in response locked ERPs, medial frontal cortex) and finally, that during RNG dorsolateral prefrontal cortex is needed to suppress habitual responses (negative effect in ERPs to standard stimuli). Further studies are needed to confirm and extend these findings.

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