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13. ABSTRACT (Maximum 200 words)

Our approach to the central executive (CE) involves combined studies of dual task interference, frontal lobe function and "general intelligence" or Spearman's g. In this reporting period we have focused on dual task interference, in particular using variants of Baddeley's (1986) random generation task, thought to load the CE because of its continual requirement for novel, non-stereotyped responding. Results suggest three main conclusions. First, the CE is modality-independent, in contrast to the peripheral "slave systems" of working memory. Second, there is a link between CE requirements and frontal lobe functions, indicated by substantial interference between random generation and a conventional frontal task, word fluency. Third, there is some tendency for tasks with high g correlations also to show the greatest interference with random generation. Taken together, these results support the convergence of methods from experimental cognitive psychology, neuropsychology and differential psychology to define a common CE system.

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Introduction

Within the working memory framework of Baddeley and Hitch (1974), the central executive (CE) has generally been seen as a high-level control system involved in the organization of many different kinds of mental activity. Beyond this, however, we lack any very precise characterization of its nature or function. The present research involves converging studies of dual task interference, individual differences in general intelligence or Spearman's g, and the behavior of patients with damage to the frontal lobes of the brain. Our hypothesis is that competition for the CE is reflected in interference between concurrent tasks, at least when they are sufficiently dissimilar to avoid more local conflicts; that individual differences in CE function are reflected in Spearman's g; and that damage to the CE is responsible, at least in part, for the disorganized behavior of frontal patients.

In the current year we have been concentrating on dual task interference, and in particular the random generation task first linked to the CE by Baddeley (1986). In this task, the subject generates responses from some fixed set, in random order and generally at a fixed pace. As a tool for investigating the CE, the task is promising since familiar, repeated or stereotyped responding is by definition inappropriate. Since James (1890) and Bryan and Harter (1899), many people have supposed that consistent practice in a stereotyped task renders high-level executive control unnecessary.

In this year's work we have addressed three issues. First, according to our hypothesis, the CE is modality-independent, in contrast to the lower-level "slave systems" of working memory. Last year we showed that verbal (random generation of spoken digits) and spatial (random generation of keypresses) versions showed similar effects of pacing; this year we go on to consider direct interference between the two, and the susceptibility of both to interference from other concurrent verbal tasks. Second, our hypothesis suggests that tasks especially sensitive to frontal lobe damage should also produce substantial interference with concurrent random generation. We consider one such task, verbal fluency, which is sensitive to frontal lesions (Benton, 1968), and activates area 46 in left prefrontal cortex in PET scanning studies (Frith, Friston, Liddle, & Frackowiak, 1991). Third, across any set of dissimilar tasks, g correlations should be closely related to dual task interference (Duncan, Williams, Nimmo-Smith, & Brown, in press). We test this prediction using a battery of 15 tasks selected from the standard ETS Kit of Factor-Referenced Tests (Ekstrom, French, Harman, & Derman, 1976).

Spatial random generation with concurrent verbal tasks

Experiment 1

Experiment 1 dealt with interference between spatial and verbal versions of random generation, and between the spatial version and verbal fluency. Each of 14 subjects served in 7 conditions (two blocks of 120 trials per condition), involving:

(i) Spatial random generation alone. Responses were made on a 10-alternative keyboard operated with fingers and thumbs of the two hands. They were to be made in random order at a rate of 1/sec in time with a metronome.

(ii) Verbal random generation alone. This task was identical, except that responses were spoken numbers 1 to 10.

(iii) Counting alone. The subject simply counted from 1 to 10 in time with the metronome, returning to the beginning each time he or she reached 10. This task was intended as a control for the input and output demands of verbal random generation, without the need to randomize.

(iv) Verbal fluency alone. Subjects generated as many items as possible from specified semantic categories. A new category was specified half way through each

120 sec block. It was emphasized that exemplars did not have to be generated in time with the metronome.

(v) Spatial and verbal random generation. One keypress and one vocal response were required at each beat of the metronome. Spatial and verbal responses were to be generated independently.

(vi) Spatial random generation with counting.

(vii) Spatial random generation with verbal fluency.

As it turned out, dual-task interference was largely reflected in performance on the spatial task, as if this task tended naturally to fall into the "background" of attention. As in our previous work, different measures of randomness gave similar results; here we present per cent digram redundancy, a measure derived from information theory which indicates the tendency to use some digrams (pairs of successive responses) more frequently than others. A score of zero is perfect (equal use of all possible digrams), while a score of 100 would indicate that only 1 digram was ever used (i.e. the same response was given throughout.) Mean scores for the spatial task are shown in Figure 1. Two results may be noted. First, the spatial task showed substantial and significant interference from concurrent verbal random generation (Newman-Keuls, $p = .01$), but none from concurrent counting. The effect of around 6% produced by concurrent verbal random generation compares with an effect of around 3% produced, in our previous experiments, by tripling generation speed from 1 keypress per 1.5 sec to 1 per 0.5 sec. Second, at 8% the effect of concurrent verbal fluency was even more substantial (Newman-Keuls, $p < .001$).

For verbal random generation, % redundancy scores were equal (17%) in single- and dual-task conditions, $F(1,13) = 0.7$. Counting produced essentially no errors and was not scored. For verbal fluency, mean numbers of items generated per category were respectively 30.3 and 28.5 in single- and dual-task conditions, $F(1,13) = 2.0$.

This experiment confirmed that there is substantial interference when spatial and verbal random generation tasks must be carried out concurrently; as required by the hypothesis of a modality-independent CE. Even greater interference with the spatial task is produced by verbal fluency, with its characteristic dependence on frontal lobe function.

Experiment 2

In Experiment 2 we explored interference between spatial random generation and reading for meaning. Subjects read passages of three different difficulty levels - as assessed by a variety of standard measures - while carrying out the standard spatial task at the 1/sec rate. Each passage took about 2 min to read, and was followed by 4 questions on its content. In separate blocks, reading and random generation were also carried out alone. Twelve subjects were tested.

Once more it was the spatial task that was most subject to dual task interference. Performance in the four conditions in shown in the first row of Table 1. There was a significant effect of condition, $F(3,33) = 7.7$, $p < .001$, due entirely to a general reduction in randomness (4-5%) produced by concurrent reading, irrespective of passage difficulty. The mean number of questions answered correctly showed a substantial effect of passage difficulty, but no significant effect of concurrent task (2.8 for reading alone vs. 2.6 with the concurrent task; $F(1,11) = 1.2$.

Once again, spatial random generation showed interference from a concurrent verbal task that was fairly substantial in comparison to the effects of generation rate in our previous work. It was somewhat smaller, though, than the interference produced by more output-intensive tasks in Experiment 1.

Experiment 3

Experiment 3 was a replication of Experiment 2 using auditorily rather than visually presented passages. Again each passage lasted for about 2 minutes, and was followed this time by 6 questions.

Performance in the spatial task is shown in the second row of Table 2. Again the significant difference between conditions, $F(3,33) = 3.1$, $p < .05$, was due largely to a general decrement (2-3%) in dual task conditions. Again this effect was rather smaller than that produced by concurrent digit generation and verbal fluency in Experiment 1. This time there was also a significant difference in the number of questions correctly answered in single (4.5) and dual (4.0) task conditions, $F(1,11) = 5.6$, $p < .05$.

Experiment 4

Experiment 4 was designed as a further test of the modality independence of the CE. The same auditory comprehension task was used as in Experiment 3, but with concurrent vocal rather than spatial random generation. The vocal task was generation of digits as in Experiment 1.

Random generation performance is summarized in the bottom row of Table 1. As in our previous experiments, digit generation was slightly easier than the keypress task, and importantly, it showed an even smaller effect (<2%) of concurrent listening, $F(3,33) = 2.7$, $p < .10$. Again, significantly more questions were answered correctly in single (4.3) than dual (3.6) task conditions, $F(1,11) = 7.7$, $p < .02$. In these data there was no suggestion that interference from concurrent listening was stronger in verbal than in spatial random generation.

Conclusions

As regards our first question, we have no evidence for modality-specificity of the CE. Verbal and spatial random generation tasks show substantial mutual interference, and the spatial task is at least as sensitive as the verbal to interference from concurrent listening/comprehension.

The strongest interference with the spatial task came from verbal fluency, with its major frontal lobe component. While this result should be replicated with a wider range of frontal tasks, it may be useful to consider what it is that fluency and random generation have in common. In fluency, a sequence of novel items must be generated in response to a fixed stimulus (the category name). The material already generated must be monitored to ensure that new material is always produced. Similar properties lie at the root of the idea that random generation avoids stereotyped responding. Again a sequence of novel output must be produced in response to a fixed stimulus (the beat of the metronome), and what has been done must be monitored to ensure that it is not related to what follows.

While a common memory component might be suspected here (storing the responses already made), other findings (described in our first annual report) suggest that it is the generation of novel output in response to a fixed stimulus that is crucial. In one of our tasks, subjects searched for the odd man out among a set of geometric stimuli varying in multiple attributes. While g correlations rapidly declined with practice if a <u>fixed</u> attribute was always relevant, they remained high when the relevant attribute (specified by verbal instruction) changed from trial to trial. Again, attribute switching meant that from trial to trial the same stimulus was to be analyzed in different ways. We also described high correlations between g and a phenomenon we have termed <u>goal neglect</u> in an attention-switching task. Here an occasional symbol instructs the subject to switch from monitoring one set of (visually-presented) letters to another; low g subjects often neglect this signal on early trials, but importantly, the phenomenon is entirely limited to novel behavior - even a single correct response causes neglect immediately to resolve.

The general rule is perhaps that CE involvement in a task rapidly declines whenever variation in the responses is associated with a correlated variation in immediate stimuli; in agreement with the general idea that "automatic" behavior can develop whenever there is a consistent mapping between some aspect of stimulus and response (Schneider & Shiffrin, 1977). In contrast, CE involvement remains high when different responses must be made to the same immediate stimulus. It is important to recognize, however, that any rule specifying a unique correct response implies consistency at some level of stimulus description (Duncan, 1986). For example, in our "odd man out" task, the combination of verbal instruction and visual stimulus is consistently mapped onto correct responses, even when relevant attribute changes from trial to trial. For this reason our question must be the sort of consistency that is effective; or complementarily, the sort of inconsistency that is common to the different tasks showing a substantial CE involvement.

Profiles of g correlation and dual task interference

Experiment 5

Experiment 5 dealt with the relationship across tasks between dual task interference and g correlations. This relationship may be considered in two different ways.

First, a task which makes heavy demands on the CE should interfere substantially with other concurrent tasks. To the extent that CE demands are reflected in g correlations, this leads to the following prediction. If a fixed secondary task X is carried out concurrently with a range of primary tasks $T_1 \ldots T_n$, then across primary tasks, the profile of performance on the secondary task X should match the profile of primary task g correlations. Primary tasks with high g correlations should lead to poor performance on the concurrent secondary task, while primary tasks with low g correlations should lead to good performance.

Though this prediction may hold approximately, it has the following difficulty. The correlations with g does not measure a task's absolute demand on the CE; rather it reflects the proportion of total between-subject variability that is attributable to g. Even a task with a low CE demand, for example, will have a substantial g correlation if it has no other significant source of between-subject variability.

The second approach bypasses such difficulties by considering not the interference that tasks $T_1 ... T_n$ produce, but rather the interference that they suffer. In this case it can be shown that, if the effect of doing one task X is to reduce each subject's effective level of g for the performance of other concurrent tasks $T_1 ... T_n$, then across $T_1 ... T_n$, dual task decrements expressed as z-scores should be exactly proportional to g correlations (Duncan et al., in press). This follows because the correlation coefficient r is defined as the slope of the best-fitting line relating z-scores on two variables; a correlation with g reflects the expected change in task performance per unit change in g.

This second approach was taken in a previous study (Duncan et al., in press). Though profiles of g correlation and dual task decrement were indeed in reasonable agreement, the study suffered from a variety of weaknesses. In particular, as tasks $T_1 ... T_n$ we used components of a familiar skill (driving a car), very much reducing the range of g correlations/dual task decrements, as well as raising questions over how measures should be scored. In Experiment 5, accordingly, we designed a replication based on a new set of tasks.

The tasks we chose were 15 standardized psychometric tests from the ETS Kit of Ekstrom et al. (1976). In this we took advantage of a U.S. Air Force study (Wothke, Bock, Curran, Fairbank, Augustin, Gillet, & Guerrero, 1991) in which 46 Kit tests were administered to very large samples of airmen. From the reported correlation matrix, we calculated each test's correlation with g defined simply as the centroid of all 46 tests. Though the centroid is somewhat sensitive to the content of a test battery, with such a large and heterogeneous set of tests it should provide a good g estimate (Spearman, 1927). For the dual task study we then selected 15 tests (Table 2), aiming for as broad as possible a spread of g correlations, minimal apparent dependence on educational level, and as diverse as possible task content.

As a concurrent task we designed a new version of random generation. To avoid local sources of dual-task interference, such as conflicts within spatial or verbal processing systems, we needed a task sharing no obvious content with the 15 Kit tests. Furthermore, we needed a task requiring neither eyes nor hands, since Kit tests were all in paper-and-pencil format. To satisfy these requirements we asked subjects to generate random <u>intervals</u> between 1 and 5 sec, by tapping on a footswitch. A pilot study suggested that this task would produce substantial interference with concurrent activities; specifically, it produced a significant decrement on concurrent word fluency.

Half the subjects (10 to date, though the complete study will have 15) performed under dual task conditions. The 15 tests were carried out once each over 3 hourly sessions, following a day of practice and familiarization. All tests were performed with concurrent random interval generation, which was repeatedly emphasized as the primary task. Remaining subjects (10 to date, matched to the first group on the Culture Fair test of g; Institute for Personality and Ability Testing, 1959) performed under single task conditions.

Unfortunately, the results suggest that attempts to render the random generation task "primary" were unsuccessful. None of the 15 ETS tests showed a significant decrement in the dual task group, and there was no hint of agreement between the nonsignificant effects observed and the profile of g correlations. For this study, therefore, we must fall back on the less satisfactory method of comparing g correlations with decrements on the random generation task.

For the interval task redundancy (the tendency to use some intervals more often than others) seemed not to be a satisfactory score. Redundancy tended to increase instead of decreasing with practice, and showed no general dual task decrement. Instead, dual task interference took the form of occasional pauses in the foot task, appearing as excessively long intervals between one tap and the next. As a measure of pauses, we took the proportion of intervals above the defined limit of 5 sec.

This proportion is shown in the upper half of Figure 2, as a function of concurrent task. The numbering of ETS tasks follows Table 2; tasks have been arranged in order of increasing g correlation. Though there is a significant tendency (r = .57) for pauses to increase with increasing g correlation of the concurrent task, the data also suggest several violations of this pattern.

A different measure of CE demand is shown in the lower half of the figure. At the conclusion of the experiment, subjects were asked to rank the 15 ETS tasks in terms of the amount of active concentration that they required. Mean ranks from the single task group - the group with no experience of concurrent random generation - are shown in the figure, lower ranks indicating less concentration. Comparing the upper and lower profiles shows substantial agreement (r = .75) between them; those ETS tasks that are rated as requiring a great deal of active concentration also produce the most interference with concurrent interval generation.

In particular, where there are violations of the predicted agreement between dual task decrements and g correlations, similar violations tend also to be seen in the ratings. Task 2, for example, has a low g correlation but a high decrement and rating, while task 11 shows the reverse. This is perhaps what we should expect if both decrements and ratings reflect a task's absolute CE demand, while g correlations instead reflect the relative contribution of the CE to between-subject variability. Task 2 - Gestalt completion, or recognizing incomplete patterns - may be used as a plausible case in point. Typically, a good proportion of patterns are recognised quickly and easily, and the subject spends the rest of the time painfully attempting the remaining patterns with little success. This second phase may be reflected in both the pause score for concurrent interval generation and the high rating for required concentration; on the other hand it may be the first phase that contributes most to the score on the Gestalt task itself, and hence to between-subject variability. Absolute CE demands and the CE's contribution to between-subject variability need not be the same.

To sum up: Though the obtained agreement between dual task decrements and g correlations is promising, the experiment was unsatisfactory because subjects were apparently unable to emphasize interval generation at the expense of the ETS tasks. To use the sounder of our two general approaches, we need a primary task that falls less easily into the "background". Meanwhile, it is gratifying that interference with a concurrent task agrees so closely with a simple rating of "demand for concentration" as a measure of absolute CE demand.

Conclusions

This year's research has led to three main conclusions:

(i) There is no evidence for modality-specific CEs. Verbal and spatial random generation show substantial mutual interference, and the spatial task suffers at least as much from concurrent comprehension.

(ii) Among the various verbal tasks carried out with spatial random generation, the strongest interference came from a task (verbal fluency) with known involvement of the frontal lobe. Consideration of the similarities between random generation and verbal fluency encourages a search for the kind of S-R inconsistency that they have in common.

(iii) Interference with random generation also tends to be strongest for tasks with high g correlations, though the data suggest several violations of this rule.

Such violations may well reflect the difference between measures of a task's absolute CE demand, and the relative contribution of the CE to individual differences. Finally, interference agrees with an explicit rating of a task's requirement for active concentration, which may also be a measure of absolute CE involvement.

Manuscripts

Duncan, J., Emslie, H., Williams, P., & Johnson, R. (submitted) Intelligence and the frontal lobe: Goal selection in the active control of behavior.

Robbins, T.W., Anderson, E.J., Barker, D.R., Bradley, A.C., Fearnyhough, C., Henson, R., Hudson, S.R., & Baddeley, A.D. (submitted) Working memory in chess.

Oral presentations

Duncan, J. Goal selection and intelligence. Working Memory Group, Berwickshire, March 1992.

Duncan. J. Intelligence and the frontal lobe. Laboratory of Neuropsychology, National Institute of Mental Health, Bethesda, May 1992.

Duncan. J. Executive functions: Theory. British Psychological Society, Cambridge, October 1992.

Emslie, H.C. Random generation and dual task interference. Working Memory Group, Berwickshire, March 1992.

Consultation

Baddeley, A.D. McDonnell Foundation Workshop on cognitive/working memory deficits following parasitic infection. New York, March 1992.

Baddeley, A.D. National Institute of Ageing Workshop on working memory, attention and ageing. Bethesda, August 1992.

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Table 1

Random generation : % digram redundancy

	Single task	concurrent passage easy	middle	difficult
experiment 2 (spatial)	.19	.24	.24	.23
experiment 3 (spatial)	.16	.19	.19	.18
experiment 4 (verbal)	.12	.13	.13	.14

Table 2

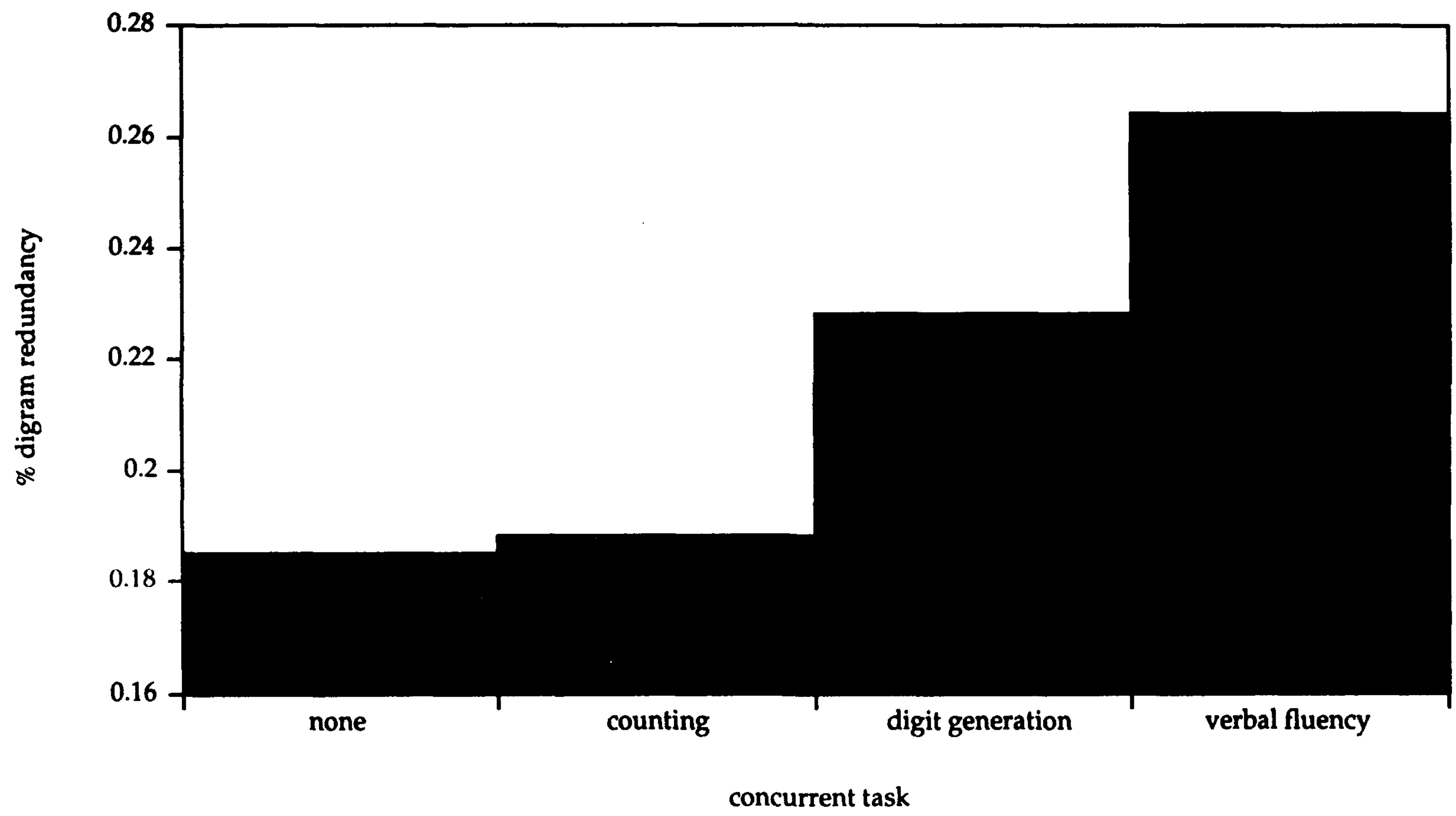
Experiment 5 : ETS tests and their g correlations

	test	g correlation
1	FF1 - Ornamentation	.26
2	CS1 - Gestalt completion	.33
3	P1 - Finding As	.35
4	MA2 - Object-number	.39
5	MV3 - Map memory	.40
6	SS1 - Maze tracing	.44
7	FI3 - Thing categories	.47
8	XF3 - Storage	.47
9	FE2 - Arranging words	.48
10	FW1 - Word endings	.52
11	CF2 - Hidden patterns	.52
12	S2 - Cube comparisons	.58
13	RL2 - Diagramming relationships	.59
14	IP1 - Calendar	.62
15	I1 - Letter sets	.65

Figure Captions

Figure 1. Experiment 1. Spatial task: per cent digram redundancy in each condition.

Figure 2. Experiment 5. Top: Proportion of errors (intervals above 5 sec) in random interval generation carried out concurrently with each of the 15 ETS tests. Bottom: Rated concentration demand for the same tests performed alone. Numbering of tests follows Table 1; g correlations increase from left to right.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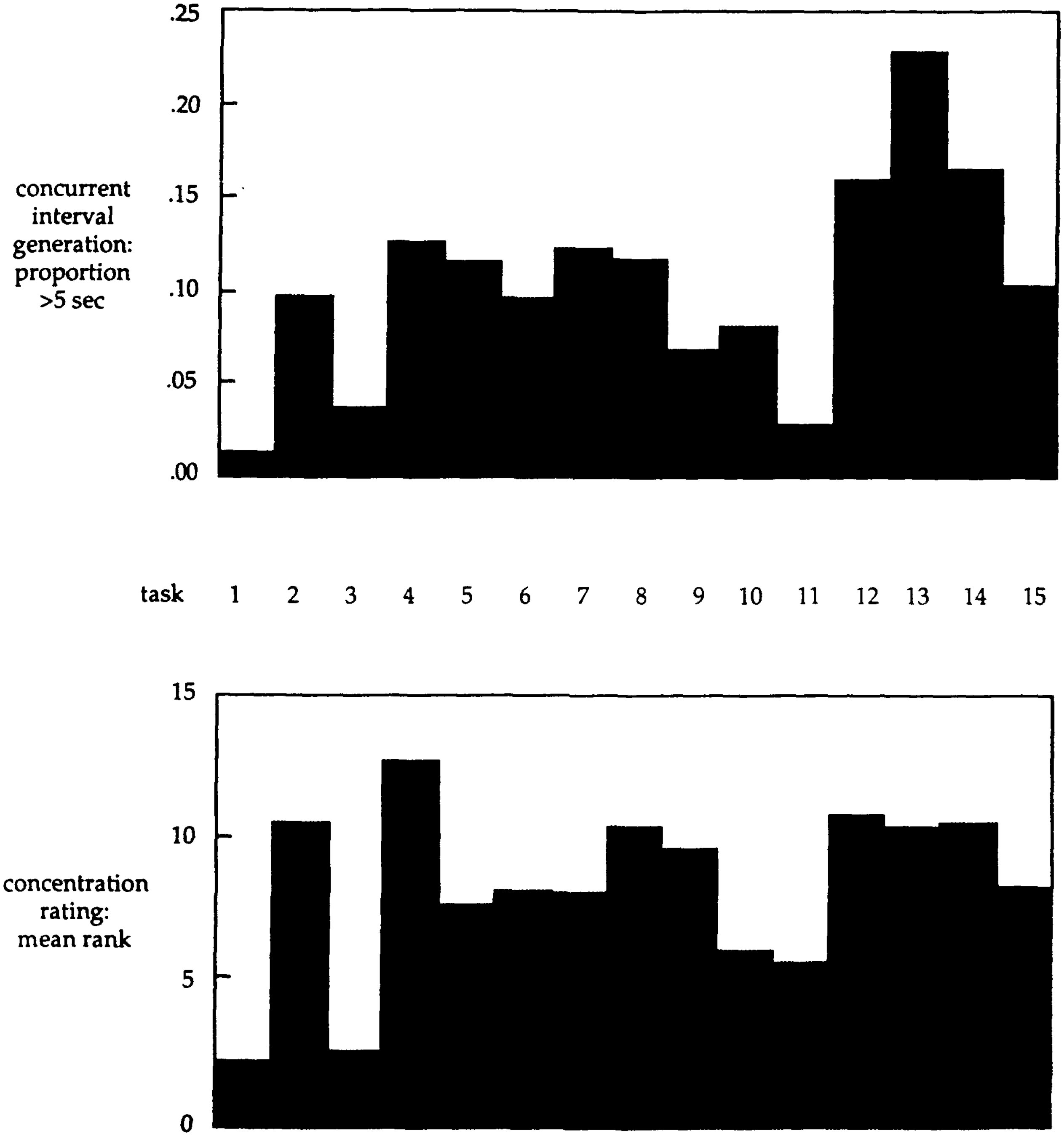
verbal fluency
concurrent task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concurrent interval generation: proportion >5 sec
task 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
15
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concentration rating: mean rank