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Is There a Specific Executive Capacity for Dual Task Coordination? Evidence From Alzheimer's Disease

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Three experiments compared groups of Alzheimer's disease (AD) patients and healthy older and younger participants on visuospatial tracking and digit sequence recall, as single tasks and performed concurrently. In Experiment 1, tasks were performed concurrently with very low demand relative to span. Only the AD patients showed a dual task deficit. In Experiment 2, single task demand was manipulated on each task from below span to above span for each individual. All groups showed the same performance reductions with increasing demand. In Experiment 3, demand on 1 task was constant, whereas demand on the concurrent task was varied. AD patients showed a clear dual task deficit but were no more sensitive than control groups to varying demand. Results suggest an identifiable cognitive resource for dual task coordination within a multiple component working memory system.

Baddeley, Logie, Bressi, Della Sala, and Spinnler (1986) reported a specific impairment in the ability of patients with Alzheimer's disease (AD) to perform two tasks concurrently. This effect did not appear to be present in normal aging, and the impairment appeared to be quite independent of any impact of the disease on the performance of each task separately. Moreover, dual task performance declined as the disease progressed, and the effect did not appear to arise from overall effects of task demand (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991). Later studies replicated the initial findings using different task combinations (Baddeley, Baddeley, Bucks, & Wilcock, 2001; Della Sala, Baddeley, Papagno, & Spinnler, 1995; Greene, Hodges, & Baddeley, 1995).

The general interpretation from these experiments was that in the early stages of AD, there is damage to some form of executive coordination function required to divide attention or to allocate specialized resources among concurrent tasks. This in turn suggested that there might be an executive dual task coordination function in the healthy brain, thereby adding to the theoretical understanding of healthy cognition as well as to the understanding of cognitive impairments in the brain damaged by AD (e.g., Della Sala & Logie, 2001). However, in reviewing the literature, Perry and Hodges (1999) noted that an interpretation of the dual task deficit in AD as a general impairment, such as in speed of processing, cannot yet be ruled out with confidence. Indeed, it has been suggested that anything that makes a task more difficult, such as a dual task requirement, will differentially impair the performance of AD patients. We addressed this possibility by exploring experimentally and systematically the impact of dual task with low demand (Experiment 1), single task with high demand (Experiment 2), and dual task in which the demand of one task was fixed while the demand of the other task was varied (Experiment 3).

Experiment 1

It is possible that the differential dual task decrement in patients reported in previous studies (Baddeley et al., 1991; Baddeley et al., 1986) reflects an interaction between task demand and the need to divide attention, rather than an overall problem with dual task coordination. A general attentional hypothesis might suggest that impairment occurs in the AD patients because their overall capacity is exceeded to a much greater extent than that of healthy adults solely by the additional demand imposed by dividing attention between two tasks. If that is the case, then reducing the level of demand of the component tasks might reasonably be expected to take the overall load below the point at which dual task performance causes impairment. However, AD patients typically perform more poorly than healthy older participants on single tasks, raising the possibility that group differences observed under dual task conditions could simply arise as artifacts of the differences in single task baseline performance (e.g., Salthouse, 1985). Therefore, we ensured that the level of demand was set according to the ability of each individual participant. In Experiment 1, we studied dual task performance, both at an individual titrated level of demand and at a level in which demand of both tasks was markedly reduced relative to each participant's ability.

Method

All patients, their caregivers, and control participants in this and all of the following experiments gave informed consent in accordance with the

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Declaration of Helsinki (World Medical Association, 2000). The experimental protocols were approved by the United Kingdom Grampian Health Board and the University of Aberdeen Joint Ethical Committee.

Participants

AD patients. The diagnostic criteria of the National Institute of Neurological and Communicative Disorders and Stroke—Alzheimer's Disease and Related Disorders Association (McKhann et al., 1984) were followed, including clinical history and neurological examination, combined with computed tomography scan and laboratory data to exclude other possible dementias. Patients were included only if they showed unequivocal evidence of deterioration as determined by neurological and neuropsychological assessment over a period of at least 6 months, had a Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) score between 15 and 25 (mild/moderate clinical stage), were less than 85 years of age, performed normally on the first two sections of the Token Test (De Renzi & Faglioni, 1978) as a measure of verbal comprehension, and were willing to take part. Patients with a history of other neurological or psychiatric diseases were excluded, as were those with evidence of chronic alcohol abuse or drug use that would possibly affect central nervous system functions.

Twenty patients with probable AD were recruited, 11 of whom failed to meet our inclusion criteria. One patient was excluded because of deafness. Therefore, 8 patients completed the experimental conditions and were included in the final analysis. This group comprised 4 women and 4 men and had a mean age of 74.1 years ($SD = 2.4$, range = 70–77), with 10 years of education ($SD = 1.4$, range = 9–12) and a mean MMSE score of 21.1 ($SD = 2.3$, range = 18–24).

Control participants. Eight older (4 female, 4 male) and 8 young (4 female, 4 male) participants completed the experiment. All of the older participants had MMSE scores indicating normal performance ($M = 28.9$, $SD = 1.3$, range = 26–30). The older group had a mean age of 72.25 years ($SD = 6.40$, range = 64–80) and a mean of 10.6 years of education ($SD = 1.8$, range = 9–14). The younger group had a mean age of 25.75 years ($SD = 6.00$, range = 21–35) and a mean of 13.9 years of education ($SD = 2.4$, range = 12–18). The older control and AD patient groups did not differ in age ($F < 1$) or in level of education ($F < 1$).

Tracking Task

Participants were asked to keep a light-sensitive stylus (light pen) placed on a red oval with dark spots (resembling a ladybird or ladybug; 2.5 cm × 2 cm) that moved at random around a computer screen. The speed of the ladybug could be set at different levels. The slowest speed corresponded to approximately 3.5 cm/s, and the difference between speed level was about 1 cm/s. For example, Level 2 speed was 4.5 cm/s, whereas Level 10 speed was 12.5 cm/s. The ladybug remained red while the light pen was in contact, but it immediately changed to green when contact was lost, returning to red when contact was regained.

Assessing individual tracking ability. The ladybug started moving slowly, at Speed Level 2. If the participant maintained contact with the target for at least 60% of the time over a period of 5 s, the speed was increased by 1 cm/s. If the participant was in contact with the stimulus for less than 40% of the 5-s period, the speed gradually decreased. If the percentage of time on target was between 40% and 60%, the speed did not change. When the speed remained constant for 15 s (three 5-s periods), this was taken as the speed level adjusted for the ability of that particular individual for use during the main experimental phase. To avoid fatigue from continuous arm movement over an extended period, the change in speed for the low levels (Levels 1–5) involved a shift of just one level at a time, whereas higher levels of speed (> 5) involved a shift of two levels.

The computer screen was placed in a specially constructed table at an angle of 30° from the horizontal, with the horizontal midpoint of the screen approximately at elbow level for a seated participant. Stimulus tracking in this arrangement was found to be less physically tiring than attempting to track on a vertical screen (Baddeley et al., 1991).

Digit Recall

Participants heard a list of digits, recorded by a female native English speaker, at a rate of 2 per s. Immediately after presentation, participants were asked to recall the digits orally in the serial order of presentation.

The initial phase for digit recall involved assessment of individual span. Participants were first presented with a sequence of two digits, and the sequence length was incremented by 1 digit after successful immediate serial-ordered recall of two out of three sequences. This process continued until the participant failed to recall at least two out of three sequences at a given sequence length. Digit span for each individual was taken to be 1 digit less than the sequence length at which he or she failed. There were no time restrictions for recall.

Main Experimental Phase

In this phase, participants performed each of the tasks on its own with demand set at their individual span and with demand set below these levels, as described below. For both tracking and digit recall, the trial for each demand condition lasted 90 s.

Tracking: Standard condition. Participants were asked to perform the tracking test for a period of 90 s at their individually assessed speed.

Tracking: Very low demand condition. In this condition, the speed level was reduced by 50% relative to the individual baseline, and tracking was performed for a period of 90 s.

Digit recall: Standard condition. Participants were asked to perform the digit recall task at their individual span as assessed in the initial phase. Sequences were presented for recall over a period of 90 s, with the total number of sequences adjusted according to the span for each individual. However, the total number of digits presented for recall was similar across all participants within the 90-s period.

Digit recall: Very low demand condition. For this condition, the sequence length was calculated by subtracting 2 from the individual span. For example, if the individual's span was 6, on the very low demand condition the participant was presented with sequences of 4 digits. Sequences were presented for recall over a period of 90 s, with the total number of sequences adjusted according to the low demand sequence length calculated for each individual. However, the total number of digits presented for recall was similar across all participants within the 90-s period.

General Procedure

First, participants were asked to perform the very low demand conditions, followed by the standard conditions. Each condition required participants to perform each of the two tasks (digit recall and tracking) as single tasks and then concurrently. The presentation order of digit recall and tracking performed as single tasks was counterbalanced across participants but remained constant across the two conditions for each participant. That is, if a participant performed digit recall first on the very low demand condition, he or she also performed digit recall first in the standard condition. The dependent variable was accuracy, that is, the percentage of time each participant remained in contact with the ladybug and the percentage of correct numbers recalled in the correct position. The first sequence of digits and the first 10 s of the tracking task were considered practice and were not included in the final analysis.

Results

Table 1 reports the digit span means and tracking speed for each group. Digit spans did not differ between the three groups ($F < 1$).

Table 1
Mean Digit Span and Adaptive Tracking Speed for Healthy Young and Older Participants and Individuals With Alzheimer's Disease (AD) in Experiment 1

Group	Digit span (*SD*, range)	Tracking speed (*SD*, range)
Young	6.7 (1.4,5.0–8.0)	17.7 (2.1,16.5–20.5)
Older	6.6 (0.7,6.0–8.0)	14.0 (3.2,8.5–18.5)
AD patients	6.2 (1.2,4.0–8.0)	12.5 (3.7,6.5–16.5)

Note. The tracking data are expressed in centimeters per second.

Tracking ability levels differed between groups, $F(2, 21) = 6.22$, $MSE = 9.40$, $p < .01$. The post hoc analysis (Newman–Keuls) showed that the AD and the older groups differed significantly from the younger group ($p < .01$ and $p < .05$, respectively), but the older and AD patient groups did not differ. The older control participants' and AD patients' tracking speed was lower than that of the younger group at similar performance levels in single task conditions.

For the tracking task, with speed set at the individually assessed level, the data from the single and dual tasks were entered into a 3 (group) × 2 (type of task: single vs. dual) analysis of variance (ANOVA). This showed a significant effect of group, $F(2, 21) = 7.16$, $MSE = 113.57$, $p < .005$; type of task, $F(1, 21) = 30.70$, $MSE = 39.38$, $p < .0001$; and an interaction, $F(2, 21) = 5.06$, $MSE = 39.38$, $p < .05$. Post hoc analysis showed a significant difference between the patients' performance on the single task versus the dual task ($p < .005$), and between the patients' performance on the dual task and performance of all the healthy participants under single and dual task conditions ($p < .005$). No significant differences were found between the single and dual task conditions for either of the control groups or between the single task performance levels of all three groups.

For digit recall with sequence lengths adjusted to the individually determined span, analyses similar to those above showed no significant main effects or interactions.

Reporting of the patterns for each individual task under dual task conditions might be misleading, given that this cannot account for the overall changes in performance across both tasks or for trade-offs in performance between tasks. Therefore, for each participant, we calculated an overall measure of performance that combined the percentage change in accuracy that occurred between the single and dual tasks for the digit and tracking tasks, according to the following formula:

$$\text{Percentage change} = \frac{\text{Single task performance} - \text{dual task performance} \times 100.}{\text{Single task performance}}.$$

Then the percentage change for each test was combined as follows:

$$\text{Combined percentage change} = 100 - \frac{(\text{Percentage change digits} + \text{Percentage change tracking})}{2}.$$

The resulting score allowed us to look at the overall impact of dual task demands, taking into account, within a single score, the overall change across both tasks between single and dual task performance (see Supplementary Figure 1 on the Web at http://dx.doi.org/10.1037/0894-4105.18.3.504.supp). The young and older groups showed decrements of 2.23% and 7.50%, respectively, whereas the AD patient group showed a decrement of 17.90%. An ANOVA yielded a significant effect of group, $F(2, 21) = 8.83$, $MSE = 57.56$, $p < .005$. Post hoc analysis showed a significant difference between the patients and the two control groups (young, $p < .001$; older, $p < .01$), whose scores did not differ.

The single and dual task data from the low demand tracking task were entered into a 3 (group) × 2 (type of task: single vs. dual) ANOVA that showed a significant effect of group, $F(2, 21) = 6.32$, $MSE = 142.56$, $p < .01$, and type of task, $F(1, 21) = 16.07$, $MSE = 69.72$, $p < .001$, but no significant interaction, $F(2, 21) = 2.50$, $MSE = 69.72$. Post hoc analysis on the main group effect showed a significant overall difference between the patients and young participants ($p < .005$), whereas the difference between the patients and older participants was marginal ($p = .06$). An ANOVA similar to that used for the tracking data was carried out on the digit data. It showed no effect of group or condition (both Fs < 1) and no interaction.

From the overall percentage change scores in the low demand condition, the younger and older groups showed overall drops of 3.34% and 2.71%, respectively, whereas the patients showed a decrement of 12.26% (see Supplementary Figure 2 on the Web at http://dx.doi.org/10.1037/0894-4105.18.3.504.supp). An ANOVA showed a significant effect of group, $F(2, 21) = 3.83$, $MSE = 59.66$, $p < .05$. Post hoc analysis showed a significant difference between the patients and both the younger ($p < .05$) and the older ($p < .05$) participants. Mean scores did not differ between the two control groups.

Discussion

Experiment 1 replicated previous findings (Baddeley et al., 1986) showing a dual task impairment in the AD group that was not present in the healthy older group. Our new low-demand procedure also yielded a difference between patients and both control groups on the combined measure of dual task impact, even with a very light overall load on the cognitive system for all participants. Such a result is at odds with theories assuming that costs in cognitive performance arise from exceeding the capacity of a single attentional resource that is damaged in AD patients.

Experiment 2

Experiment 2 was limited to single task performance, exploring a range of levels of demand, both below and above the standard span length. The aim of the experiment was to study the effect of systematically increasing the level of difficulty on the performance of the three groups, under single task conditions, with no requirement to divide attention. If the previously observed deficits in AD patients stemmed from a general limitation in processing capacity, then they should show an increasing divergence from control performance as the level of difficulty of the single task increases. Conversely, if our prior effects were specific to dual task performance, then no such divergence would be expected.

Method

Participants

AD patients. Of 12 patients initially recruited, 8 (5 female, 3 male) fulfilled the inclusion criteria; they had a mean age of 75.2 years (*SD* = 4.9, range = 68–82) and a mean of 11.2 years of formal education (*SD* = 3.3, range = 9–17). Their mean score on the MMSE was 21.9 (*SD* = 2.3, range = 17–24).

Control participants. Eight older (5 female, 3 male) and eight younger (4 female, 4 male) participants with no history of neurological or psychiatric disease were recruited. The older group performed the MMSE in the normal range (*M* = 29.5, *SD* = 1.3, range = 26–30). Their mean age was 73.0 years (*SD* = 6.5, range = 63–80), and they had a mean of 13.9 years of education (*SD* = 3.4, range = 9–20). The young group had a mean age of 26.6 years (*SD* = 5.6, range = 20–34) and a mean of 13.3 years of education (*SD* = 1.6, range = 12–16). Age and education did not differ significantly between the AD patients and the older group.

Tasks and Procedures

The tasks were the same as those used in Experiment 1, including an initial phase to assess individual levels of tracking ability and digit span for each participant.

Main Experimental Phase

In this phase, participants performed only single tasks at five different levels of demand covering the range below, at, and above the level assessed for each individual and for each task. These are referred to below as *very low demand, low demand, standard, high demand,* and *very high demand.* For the tracking task, the five different levels of target speed comprised proportions (0.50, 0.75, 1.00, 1.25, 1.50) of the standard level of tracking speed assessed for each individual. For example, if a participant reached Speed Level 20 for tracking, the speed levels for the five experimental conditions were 10, 15, 20, 25, and 30, respectively. When the fraction of a level did not produce a whole number, a correction for the underestimation of the low/very low demand conditions and the overestimation of the high/very high demand conditions was made (for example, with a standard level of 26, the corresponding levels were 13, 19, 26, 33, and 39). Each trial at a given speed level lasted for 90 s without interruption. The dependent variable was time on target, taken as the percentage of time that the light pen remained in contact with the ladybug. The first 10 s of each 90-s trial were treated as initial practice and were not included in the final analysis.

For digit recall, the five sequence lengths for each individual comprised Span – 2, Span – 1, Span, Span + 1, and Span + 2, calculated in each case relative to the span as assessed for each individual. For example, with a span of 5, the sequence lengths for each condition were 3, 4, 5, 6, and 7, respectively. Participants were tested for 90 s, during which they heard a series of lists of digits for immediate serial-ordered oral recall. The sequence length for each list was fixed for each individual according to their digit span as measured in the initial phase. A period of 1 s for each number presented was allowed for recall. The number of sequences presented within each 90-s period was determined by the length of the sequence for each individual. However, the total number of digits across all lists presented was very similar for all participants. The dependent variable was the percentage of correctly recalled digits in the correct position. The first sequence was considered a practice trial and was not included in the final analysis. All participants performed all five conditions for one task, starting with very low demand, with demand increased gradually to very high demand. Then participants performed the five single test sections of the other task in the same order of demand. Presentation order of digit and tracking tasks was counterbalanced across participants.

Results

The mean scores for digit recall span and for tracking are shown in Table 2. Digit spans showed a significant effect of group, $F(2, 21) = 5.30$, $MSE = 0.88$, $p < .05$. Post hoc pairwise comparisons of means indicated that patients differed significantly from both of the control groups ($p < .05$), but that the older group did not differ from the younger group. This difference in initial level of performance reinforced the argument that we should undertake group comparisons on the basis of relative, rather than absolute, differences in performance across levels of demand for digit recall. The same analysis on mean levels of tracking speed showed no significant difference between the groups.

The performance of each group on single task tracking in the main experimental phase is shown on the left of Figure 1. The effect of demand is evident for all three groups. Performance under very low demand was similar across groups, as was the drop in percentage accuracy across the five conditions. In the single tracking test, young participants showed a total drop in performance of 62.31% between the lowest demand (89.65%) and the highest demand conditions (27.34%); older participants showed a drop of 63.61% (88.94–25.33%), and for the AD patients, the drop was 57.34% (83.73–26.39%).

The left section of Figure 2 displays the data for digit recall. The younger group showed a total drop in percentage accuracy across the full demand range of 41.41% (97–55.59%), with the equivalent figure for the older group being 52.01% (98.41–46.40%), and for the AD patients, 51.18% (98.19–47.01%), indicating that the variation in demand led to a very similar decrement in performance across all three groups. The standard deviations for the tracking and digit tests are shown in Table 3.

The mean percentage times on target for the tracking test were entered into a 3 (group) × 5 (levels of demand) ANOVA. The demand effect was significant, $F(4, 84) = 477.90$, $MSE = 31.60$, $p < .0001$, whereas neither the group differences nor the Group × Demand interaction were significant ($F < 1$). A post hoc analysis showed that each level of demand was significantly different from all others ($p < .0001$). It is possible that there might have been evidence of a divergence in performance between the AD and the other two groups when demand exceeded the individually determined capacity task performance. Were this the case, we might expect that the high demand and very high demand conditions would be the most sensitive to such an effect. However, the effect size (η^2) for the between-group difference was 0.0197 for the high demand condition and 0.0226 for the very high demand condition. Both effects are extremely small (Cohen, 1988), indicating that the lack of a differential effect between groups was not due to a lack

Table 2
Mean Digit Span and Adaptive Tracking Speed for Healthy Young and Older Participants and Individuals With Alzheimer's Disease (AD) in Experiment 2

Group	Digit span (*SD*, range)	Tracking speed (*SD*, range)
Young	7.7 (0.5,7.0–8.0)	15.2 (3.0,8.5–18.5)
Older	7.2 (1.2,5.0–8.0)	14.2 (1.3,12.5–14.5)
AD patients	6.2 (1.0,5.0–7.0)	12.5 (2.6,8.5–16.5)

Note. The tracking data are expressed in centimeters per second.

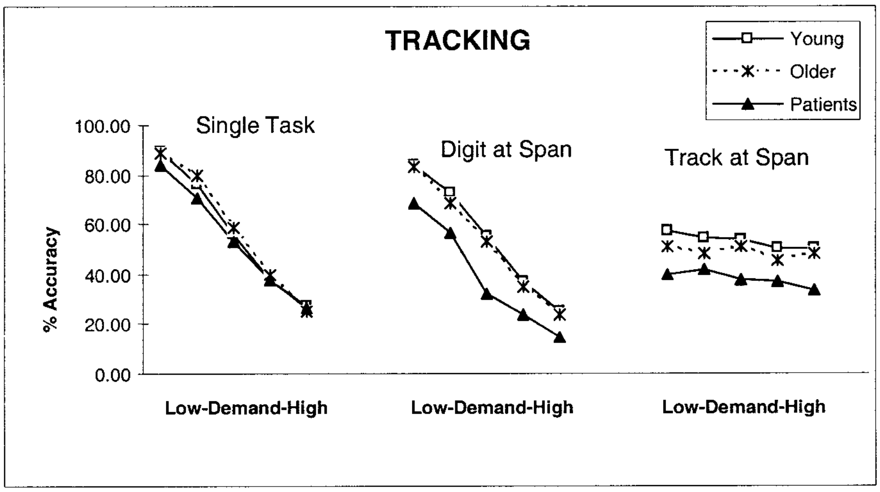

Figure 1. Mean percentage of time on target for tracking with (a) tracking performed alone and tracking demand varied (single task), (b) tracking demand varied concurrently with recall of fixed length sequences of digits (digit at span), and (c) tracking demand fixed concurrently with recall of varied length sequences of digits (track at span) for three groups of participants in Experiments 2 and 3.

of power in the experimental design and emphasizing that there is clearly no evidence that the performance patterns between groups diverged as demand of single task tracking exceeded the measured tracking ability of each individual taking part.

When the digit recall task was performed on its own, the demand effect was again the only significant variable, $F(4, 84) = 117.30$, $MSE = 89.10$, $p < .0001$. Post hoc analyses showed that all the levels of demand differed significantly from one another (all *p*s $< .0005$). The only exception was that the difference between the two lowest demand conditions was not significant. The between-group effect size was 0.1080 for the high demand condition and 0.0985 for the very high demand condition. Both of these are small effect sizes (Cohen, 1988), again indicating that our results were not due to insensitivity in the experimental design, suggesting that there is no evidence that performance of digit recall was differentially affected across groups by sequences that exceeded the span for each individual.

Discussion

Experiment 2 demonstrated that participants in all three groups showed very similar effects on performance of a systematic in-

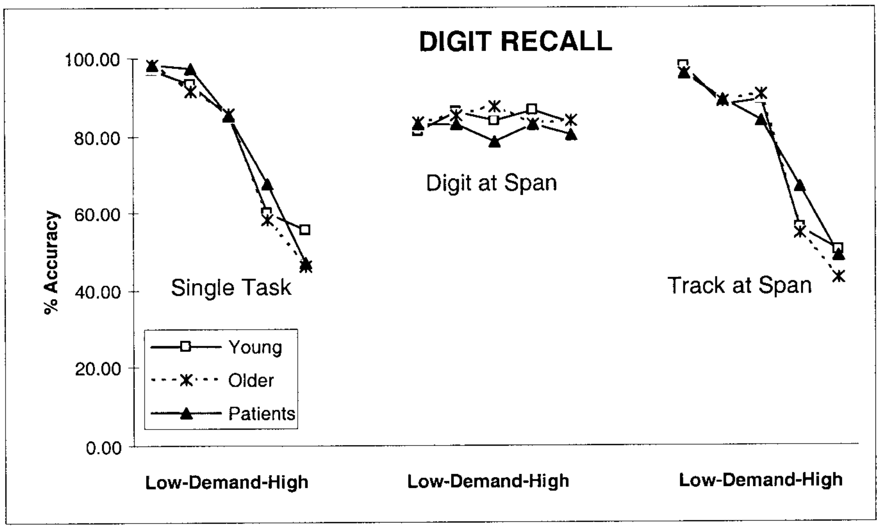

Figure 2. Mean percentage of correct digit recall with (a) recall performed alone and sequence length varied (single task), (b) recall of fixed length sequences of digits concurrently with tracking demand varied (digit at span), and (c) recall of varied length sequences of digits (track at span) concurrently with tracking demand fixed for three groups of participants in Experiments 2 and 3.

Table 3

Standard Deviations of Mean Time on Target for Tracking and Mean Digit Recall Performance Across Different Demand Levels for the Three Groups in Experiment 2

	Tracking task			Digit task		
Demand level	Young	Older	AD patients	Young	Older	AD patients
Very low	5.2	5.1	8.6	3.3	1.8	5.1
Low	8.5	7.1	7.9	5.5	6.9	5.3
Standard/at span	5.8	6.5	6.7	10.6	3.9	4.1
High	5.5	3.6	10.1	10.7	11.7	15.6
Very high	5.6	6.0	5.8	13.4	16.1	10.6

Note. AD = Alzheimer's disease.

crease in demand in either the speed of tracking required or in the length of digit sequence to be recalled. There was no evidence of a differential impairment in the AD patient group—a result that contrasts with the differential impairment found previously for AD patients—when two tasks were performed concurrently (e.g., Baddeley et al., 1991; Baddeley et al., 1986). In summary, Experiment 2 provided no support for the hypothesis that simply increasing level of task demand would differentially impair AD patients' performance in the absence of the requirement to divide attention. Taken together with the results from Experiment 1, showing that the performance of two low demand tasks resulted in a specific impairment in the AD patients, the findings support the hypothesis of a cognitive function engaged for meeting the challenge of dual task performance and that this function is specifically impaired in people with AD.

A remaining issue is whether the lack of an effect in the AD group of overall single task demand might appear under high demand, dual task conditions. One means to address this is to assess the impact of varying task demand on one task while demand on the other task remains fixed at individually adjusted levels for each participant. Experiment 2 demonstrated that patients could cope with a range of demands below and above span. That is, although the task demands were well above individual span, AD patients were still able to perform above floor levels. As such, the performance levels in Experiment 2 established the feasibility of a final experiment in which we systematically varied the demand within a dual task paradigm for both healthy individuals and those with AD.

The manipulation described above should ensure that each participant performs at and beyond his or her capacity under dual task conditions, thereby offering a design that might be more sensitive to a possible interaction between demand and divided attention. However, if the manipulation of the demand on one task is found to have little or no impact on performance of the concurrent task in control participants or individuals with AD, then we might feel more confident that dual task cost and overall cognitive demand posed by each task are supported by separable components of the cognitive system in both the healthy and the damaged brain. For the AD patients, on the one hand, if their dual task decrement stems from a general limitation in processing capacity, then it should be particularly apparent as the load on the two constituent tasks increases. On the other hand, if the deficit occurs because of a specific difficulty in combining performance, then one might reasonably expect the effect to remain constant across levels of demand for each task. Therefore, in Experiment 3, we extended the previous experiments by studying dual task performance across a range of levels of demand.

Experiment 3

Method

Participants

The participants were those who took part in Experiment 2.

Test and Procedures

The tasks were the same as those used in the previous experiments. In this experiment, participants were asked to perform the dual task over five different levels of demand, with the manipulation of demand as described for Experiment 2. Two blocks, each with five different trials, were given. During Block 1, the level of demand for the tracking task (primary test) was fixed at the speed assessed for each particular individual participant, whereas the demand of the digit task (secondary test) changed through the five levels of demand (from very low demand, through individually assessed level, to very high demand). During Block 2, the demand of the digit task (primary test) was fixed at the individually assessed level, whereas the demand for the tracking task (secondary test) changed through the five levels of demand, ranging from well below the assessed level, through that level, to well above the assessed level for the individual. The entire experiment consisted of 10 trials of 90 s each, 5 in each block. The presentation order of the two trial blocks was counterbalanced across participants.

As in previous experiments, the dependent variables were the percentage of time each participant remained in contact with the ladybug target and the percentage of digits recalled in the correct position. The first sequence of digits and the first 10 s of the tracking task were not included in the final analysis.

Results

Figures 1 and 2 show the performance on the dual task tracking and digit tests. The plots in the center of each figure represent tracking and digit task performance, respectively, when the demand of tracking was manipulated while digit recall was performed at the fixed sequence length of each individual's span. The plots on the right of each figure indicate the performance pattern when the cognitive demand on digit recall was manipulated while tracking was performed at the fixed individual level for target speed. The standard deviations are reported in Table 4.

Table 4

Standard Deviations for Tracking and Digit Recall Under Dual Task Conditions, With Task Demand Varied, for the Three Groups in Experiment 3

	Tracking dual task			Digit recall dual task		
Condition	Young	Older	AD patients	Young	Older	AD patients
Tracking demand varied						
Very low demand	7.83	6.54	21.35	10.21	8.76	8.61
Low demand	5.65	8.93	18.61	7.51	8.15	17.62
Standard	5.43	6.87	18.11	11.96	8.01	8.76
High demand	5.75	6.01	13.34	8.16	9.20	10.30
Very high demand	6.77	5.79	10.53	14.70	6.36	12.52
Digit recall demand varied						
Very low demand	5.92	7.74	12.18	3.03	6.33	6.03
Low demand	5.44	6.98	10.24	12.14	9.32	11.72
Standard	7.94	6.07	10.42	7.37	6.41	10.52
High demand	8.01	8.05	14.89	16.44	14.50	12.08
Very high demand	8.62	8.62	14.57	18.47	10.49	11.11

Note. AD = Alzheimer's disease.

The data shown as the middle plot of Figure 1 indicate that tracking performance decreased as the cognitive demand for tracking was increased, whereas demand on digit recall did not change. From the right-most plot of Figure 2, it is clear that changing digit sequence length resulted in a deterioration in the percentage of digits recalled correctly, against a background of a concurrent fixed demand for the tracking task. It is notable that dual task performance in both of these conditions was very similar to that found for performance of each respective single task (left plot in each figure).

Mean percentage times on target for the tracking task (left and middle plots, Figure 1) were entered into a 3 (group) × 2 (single vs. dual) × 5 (levels of demand) ANOVA. All three variables were significant: group, $F(2, 21) = 5.79$, $MSE = 376.97$, $p < .01$; single versus dual, $F(1, 21) = 24.67$, $MSE = 148.43$, $p < .0001$; and demand, $F(4, 84) = 469.06$, $MSE = 60.91$, $p < .0001$. Also, the interaction between the group and single versus dual factors was significant, $F(2, 21) = 5.93$, $MSE = 148.43$, $p < .01$. The interaction between the single versus dual and demand variables was marginal, $F(4, 84) = 2.29$, $MSE = 19.58$, $p < .07$, as was the three-way interaction, $F(8, 84) = 1.8$, $MSE = 19.58$, $p < .09$, whereas the interaction between the group and demand factors was not significant ($F < 1$). Effect size for the Group × Demand interaction was 0.094, which is a small effect (Cohen, 1988), indicating that the lack of an effect was not due to lack of power in the experimental design. A post hoc pairwise analysis on the means for demand showed that there were significant differences between all conditions (all *p*s $< .0001$). Post hoc analysis for the Group × Single Versus Dual interaction showed a significant difference for the patient group between the single and dual conditions ($p < .001$) and between the dual task performance for the patients and all the other conditions for the healthy participants (all *p*s $< .001$). No significant differences were found between single and dual task performance for either of the healthy groups.

A 3 (group) × 2 (single vs. dual) × 5 (levels of demand) ANOVA was carried out with the digit recall task data (left- and right-most plots in Figure 2). Only the effect of demand was found to be significant, $F(4, 84) = 186.39$, $MSE = 114.98$, $p < .0001$. In particular, there was no interaction between group and level of demand, $F(8, 84) = 1.66$, $MSE = 114.98$, *ns.* This interaction gave an effect size of 0.158, indicating that an interaction might have been obtained with slightly higher power in the design, but such an interaction would be very modest at best, and the dominant feature of the data is clearly the main effect of overall demand. The post hoc analysis showed that there were significant differences between all levels of demand ($p < .05$).

A second series of analyses investigated the effect of changes in a task varying in demand on performance of a task for which demand was fixed (right-most plot in Figure 1 and middle plot in Figure 2). First, we considered performance on tracking when it was performed at the individual level of ability while the digit recall task demand (sequence length) was manipulated (right plot in Figure 1). A 3 (group) × 5 (demand) ANOVA showed a significant effect of group, $F(2, 21) = 6.80$, $MSE = 357.28$, $p < .005$, and a significant effect of varying demand, $F(4, 84) = 5.62$, $MSE = 22.90$, $p < .001$. The interaction was not significant, $F(8, 84) = 1.16$, $MSE = 22.90$, *ns,* with an effect size of 0.111, indicating that even with higher power, any effect would have been modest. Post hoc analysis of the group effect showed that performance by the AD patients differed significantly from that of the older ($p < .05$) and younger ($p < .005$) participants, but the groups of healthy participants did not differ from one another.

Similar analyses were conducted for the digit recall data with demand (sequence length) set at the individual span while the tracking test demand was manipulated from very low demand to very high demand (middle plot in Figure 2). No significant effect (group, demand, or interaction) was found ($F < 1$).

Finally, we examined the combined percentage decrement score, calculated as described in Experiment 1. For Experiment 3, the formula combined the percentage change between the single task performance for each condition and its corresponding dual task. For example, the first combined score was derived by comparing the percentage change between the single and dual tasks in the very low demand condition, both for tracking and for digit recall. The procedure used in this experiment yielded two scores for the standard (at span) condition for each participant, and a mean value was calculated (see Supplementary Figure 3 on the Web at http://dx.doi.org/10.1037/0894-4105.18.3.504.supp). These were entered into a 3 (group) × 5 (demand) ANOVA that showed a significant effect of group, $F(2, 21) = 3.51$, $MSE = 542.70$, $p < .05$, whereas there were no significant effects of demand or of the interaction ($F < 1$). Post hoc analysis for the group variable showed a significant difference between the older and AD groups ($p < .05$). No difference was found between the two control groups.

Discussion

Experiment 3 showed an overall reduction in performance for all three groups with increasing task demand. Again, we found differential impairment in dual task performance across groups, with the AD patients showing a disproportionate degree of decrement. As in Experiment 1, we found that the differential decrement appeared in tracking rather than in digit recall. Most important, there was no evidence of an interaction between dual task demand and dual task decrement. Such a result suggests a specific effect of the need to perform two tasks concurrently that is quite independent of overall cognitive demand.

The lack of a differential impact of demand across groups cannot readily be explained by nonhomogeneity of variance between the groups or general insensitivity of the design. Because we used individually assessed levels of task demand and compared performance against baseline for each individual, differences in baseline performance were unlikely to affect the results. Moreover, because we set demand level on the fixed-demand task at each individual's maximum assessed performance capacity, this ensured that the lack of any differential effect of secondary task demand cannot be explained in terms of participants being at ceiling on one of the tasks, thereby allowing spare capacity for secondary task demand. Nor were performance changes restricted by a performance floor. Finally, it is clear that the design was sufficiently sensitive to detect a clear impact of varying secondary task demands across all three groups and to demonstrate a between-groups main effect of any kind of dual task manipulation, regardless of the levels of demand for each task. These results are therefore inconsistent with both a simple overall capacity interpretation and with the proposal of an interaction between dual task performance and level of load.

General Discussion

Our overall goal in these studies was to investigate further the hypothesis of a specific mechanism engaged for dual task performance. Our approach was to explore a related hypothesis that individuals with AD show a specific deficit in dual task performance that cannot readily be explained by the impact of general cognitive demand or of limitations in general cognitive capacity. Support for this hypothesis would indicate impairment in the individuals with AD of a specific dual task coordination function that is a component of the cognitive system in the healthy brain. This was contrasted with an alternative hypothesis that represents a more general account of cognitive function in terms of a single limited-capacity processing system, coupled with the assumption that the more difficult the task, the more sensitive it will be to AD.

The alternative hypothesis is based on the assumption of a general deficit in cognitive function in AD. If a general cognitive-limitations hypothesis is to have any theoretical value, then it seems reasonable to suggest that it would make predictions about the impact of manipulating task demand above and below the capacity limitations for each task as assessed for each individual participant. A deficit in such a general-purpose resource should be especially sensitive to a manipulation of task demand. In Experiment 1, as predicted by the dual task hypothesis, the requirement to divide attention impaired only the performance of the patient group, even with a very low overall cognitive load. In Experiment 2, we observed that increasing level of demand of a single task impaired performance in all three groups to an equivalent extent relative to a common baseline. This showed that performance was sensitive to the manipulation of task demand, but the complete lack of a differential effect on the AD group gave no support for the hypothesis that task difficulty will, in general, differentially impair their performance. Finally, Experiment 3 offered no evidence for an interaction between dual task cost and overall load as predicted by the general capacity hypothesis. In summary, our results are entirely consistent with the assumption of a specific AD deficit in dual task performance.

In Experiments 1 and 3, the clearest dual task effects appeared in the tracking task rather than in the digit recall task. It is possible that if the cognitive impairment suffered by the AD patients is restricted to their ability to perform two tasks concurrently, then they may attempt to protect performance on one task at the expense of performance on the other task. This would be a rational approach to a realization that they cannot adequately perform both. One possible account arises from spontaneous reports by patients and their caregivers. In the case of digit recall, the participants have to respond orally to an experimenter, making their impairments in performance salient to another individual. Performance on tracking is recorded by a computer, and they may feel that their poor performance on tracking is less obvious to the experimenter. Patients in the early stages of AD are aware that they have cognitive problems, and they may wish to give the experimenter the impression that they can still perform at a reasonable level. This often motivates them or their caregivers to agree to participate. Indeed, they do perform at a reasonable level under single task conditions and can approximate single task conditions when faced with a dual task demand by focusing on one task rather than the other. This reinforces the value of using a combined measure of changes in both tasks.

We found little evidence of age-related effects on dual task performance, adding to the debate in the literature. Interpretation of such effects is complicated by the absence in many studies of attempts to match groups on initial levels of performance on the individual tasks. Combining two tasks, both of which show an age effect, will inevitably demonstrate an age effect on dual task performance. Even when the combined performance levels show a greater decrement than would be predicted from the age-related decline on the individual tasks (Fernandez & Moscovitch, 2000; Naveh-Benjamin, Craik, Perretta, & Tonev, 2000), the interpretation remains problematic (Perfect & Maylor, 2000). It may prove possible, under some conditions, to detect age differences in dual task performance even when the constituent tasks are matched for level of difficulty across groups. However, our own results, and the equivocal nature of the findings within the existing literature, suggest that any such age effects are not as robust as the consistent dual task decrement observed in AD patients. This argues that the effect is specific to AD compared with healthy aging. Whether this specific effect appears in other forms of dementia remains a topic for further research.

It is becoming clear that the dementias are not associated with a global cognitive deficit, but rather indicate dissociable components of cognitive function, both across and within types of dementia (e.g., Perry, Watson, & Hodges, 2000). For AD, the principal symptom of an episodic memory deficit often is accompanied by an attentional deficit (Perry & Hodges, 1999). From the new data, the attentional deficit appears to be fractionable, with the capacity to divide attention being particularly susceptible, and the capacity for coping with increased overall demand less affected. This reinforces the view that executive control reflects a range of processes in the healthy brain (e.g., Baddeley & Logie, 1999; Lovett, Reder, & Lebiere, 1999; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000) rather than a single, general-purpose control mechanism (e.g., Cowan, 1999; Kane & Engle, 2002). Specifically, AD patients appear to suffer from impairment of a cognitive function used in the healthy brain for supporting dual task performance.

We might also consider the neuroanatomical correlates of dual task performance. In healthy adults, functional MRI (fMRI) techniques indicate that a range of neuroanatomical areas, with different paradigms, are associated with a specific dual task demand. Common to many studies is the finding that the lateral prefrontal cortex and the anterior cingulate are activated during performance of task switching and concurrent dual task demands, respectively (see review in Dreher & Grafman, 2003). In AD, the early stages of the disease are associated with gray matter loss in the retrolandic areas, with a spread to more frontal cortical areas at later stages (e.g., Thomson et al., 2003). This progression of damage over time would be consistent with the finding that episodic memory deficits appear first, with the dual task deficit and general attentional impairments associated with disease progression (Perry et al., 2000). However, this neuroanatomical interpretation of our findings is speculative, and it is complicated by the possibility that other forms of neurological pathology, for example the changes in tau protein or a modification in neurotransmitters, do not necessarily show the same pattern of progressive loss. Moreover, retrolandic damage might have indirect effects on the efficiency with which intact prefrontal areas can operate because of the need to compensate for the more posterior atrophy; because effective functioning of the frontal areas relies on input from the posterior areas (e.g., Spinnler, 1991); or because dual task coordination requires an intact neuroanatomical network, and damage to any part of that network will result in performance impairments (see Balota & Faust, 2001) regardless of the precise locus of that damage.

Finally, what precisely might a dual task coordination function comprise? Our own theoretical framework assumes that several cognitive functions support online cognition. These components collectively form a working memory system involving a range of executive control functions and domain-specific temporary memory systems. Our results are wholly consistent with this multiple resource model of working memory, and they provide evidence for an executive function involved specifically in dual task performance. We have chosen to combine digit recall and tracking, each of which is thought to use different, domain-specific systems within working memory. One possibility is that performing two such tasks concurrently requires some form of coordination function, responsible for initiating the activity of each domain-specific system, monitoring its ongoing functioning, and ensuring effective transfer of sensory input to the relevant domain-specific system (e.g., encoding) and generation of output from such systems (e.g., retrieval). Although this general interpretation might be speculative at this stage, it offers an additional set of hypotheses that might be tested in future studies. However, what appears clear from the three experiments reported is that not only do they offer additional insight into the cognitive impairments suffered by individuals with AD, but they also provide evidence for the characteristics of at least one executive function engaged to address the demands of concurrent task performance.

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