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Merat, N. and Groeger, J.A. (2003) Working memory and auditory localization: demand for central resources impairs performance. The Quarterly Journal of Experimental Psychology Section A, 56 (3). pp. 531-549. ISSN 1747-1226

https://doi.org/10.1080/02724980244000521

Published paper
Merat, N., Groeger, J.A. (2003) *Working memory and auditory localization: demand for central resources impairs performance.* Quarterly Journal of Experimental Psychology. 56A(3) 531-549

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2003, *56A* (3), 531–549

Working-memory and auditory localization: Demand for central resources impairs performance

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Four experiments explored possible roles for working memory in sound localization. In each experiment, the angular error of localization was assessed when performed alone, or concurrently with a working-memory task. The role of the phonological slave systems in auditory localization was ruled out by Experiments 1 and 2, while an engagement of central resources was suggested by the results of Experiment 3. Experiment 4 examined the involvement of visuo-spatial systems in auditory localization and revealed impairment of localization by the concurrent spatial working-memory task. A comparison of dual-task decrement across all four studies suggests that localization places greater demand on central than on spatial resources.

Our ability to identify the source of an auditory stimulus has been studied extensively in both humans and animal models (King & Palmer, 1983; Middlebrooks & Green, 1991). Results from these studies have established that accurate auditory localization is achieved by the filtering effects of the pinnae and is due to differences in the timing and intensity of a sound source heard by each ear. These neurophysiological studies have also established that accurate localization is best accomplished with broadband sounds such as white noise, since they provide a richer source of spectral cues for "combination and comparison" (Wightman & Kistler, 1993). Indeed, psychoacoustic research has shown that we can localize some sound sources quite accurately—within about 4° for broadband sounds presented directly ahead of us at ear level (Blauert, 1997).

However, while the physiology of sound localization is well understood, further research is required to understand the processes involved in identifying and remembering the position of

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This work was supported by a studentship to the first author from the Economic and Social Research Council, which was sponsored by Sound Alert Ltd. The authors wish to thank Robert Logie and Neil Ingham for their helpful comments on earlier drafts of this paper. We are also grateful to Deborah Withington for access to laboratory facilities, as well as David Horton and John Varley for their technical support.

http://www.tandf.co.uk/journals/pp/02724987.html DOI:10.1080/02724980244000521

auditory events for short periods of time. Moreover, there is currently little information on the effect of other, competing, tasks on auditory localization. This paper describes the results of four experiments designed to test some of the above issues, by employing a dual-task approach, used extensively within the working-memory framework. This approach assumes that if two tasks require the same working-memory resource, then performance in one or both tasks will deteriorate when they are performed together, compared to when each task is performed alone. Therefore, as well as establishing the effect of competing/concurrent tasks on the accuracy of auditory localization, this approach also sought to determine the possible role of working-memory in sound localization.

The working-memory model, initially proposed by Baddeley and Hitch in 1974, has become a powerful tool for understanding the process by which information is stored and manipulated in memory for short periods of time. Since its introduction, the model has been used extensively in studies of cognitive psychology, in tests of neuropsychological patients (see Becker, 1994), and within neuroimagery research (Paulesu, Frith, & Frackowiak, 1993; Smith & Jonides, 1997). Within this framework, auditory verbal material is thought to be maintained by the phonological loop, which consists of a passive phonological store and an active articulatory rehearsal process. However, the fact that the "unattended speech effect" (i.e., reduced ability to remember visually presented material in the presence of irrelevant background speech) has been shown to extend beyond speech-like material (e.g., tones, see Jones & Macken, 1993; and instrumental music, see Salamé & Baddeley, 1989) is suggestive of the involvement of the phonological loop in other sound-based tasks. The other major subsystem, the visuo-spatial sketch pad (VSSP), is thought to consist of a passive visual cache and an active spatial rehearsal process called the inner scribe (see Logie, 1995), which is also thought to play a part in maintaining kinaesthetic information (e.g., Smyth & Pendleton, 1990; Woodin & Heil, 1996). The operation of these two subsystems is thought to be coordinated by an attentional control system, the central executive. This component is not believed to have a storage capacity, but as well as an ability to activate information from long-term memory, it is thought to play a supervisory role in task switching within dual- or multi-task situations (Baddeley, Emslie, Kolodny, & Duncan, 1998). While the explanatory and predictive power of the working-memory model has been demonstrated in a wide range of experimental and applied contexts, there is relatively little research concerned with a systematic examination of whether and how each component of working-memory copes with auditory localization. For instance, it is possible that both the spatially based and the sound based subsidiary systems of working-memory are required in a localization task, and that when the localization task increases in difficulty (i.e., when precision or discriminality of localization is required) there may also be a substantial requirement for executive processes.

When considering the spatial characteristics of the VSSP, only a handful of studies on the working-memory model have used an auditory-based task (e.g., Baddeley & Lieberman, 1980; Smyth & Scholey, 1994). For instance, in an attempt to determine whether *spatial* or *visual* coding is used by the VSSP, Baddeley and Lieberman studied the effects of both a visual and a spatial task on performance of Brooks matrix, which is an imagery task thought to rely on visuo-spatial working-memory resources (Brooks, 1967, 1968; but see Salway & Logie, 1995). Subjects were asked to remember the position of a series of digits in a 4 × 4 matrix, using either visuo-spatial or verbal coding. During the concurrent dual-task condition, subjects either tracked the position of a sound-emitting pendulum (the spatial task) or judged the brightness of a series of lights (the visual task). Brooks spatial matrix was found to be impaired by tracking the path of the acoustic pendulum, but concurrent tracking failed to impair memory by verbal coding. Also, the nonsense task was impaired more than the spatial task by concurrent brightness judgment, leading Baddeley and Lieberman to conclude that spatial rather than visual coding is used by the VSSP.

In a later experiment, Smyth and Scholey (1994) used auditory stimuli to study the effect of shifts in spatial attention on performance of the Corsi blocks—a task believed to engage immediate spatial memory (De Renzi & Nichelli, 1975). In the Corsi blocks task, subjects are asked to observe the tapping of a sequence of blocks by the experimenter and then recall the sequence following a retention interval. Smyth and Scholey (1994) found an impairment of the Corsi blocks by a series of six tones, presented to the left or right of the subject's head during the retention interval. This disruption was observed both when subjects had to identify the location of each tone (by pointing to the left or right) and when subjects were simply required to listen to the tones. Smyth and Scholey conclude that such disruption of the Corsi blocks was due to attentional shifts, brought about by the auditory stimuli.

However, Klauer and Stegmaier (1997) attribute this disruption of Corsi blocks by dichotic presentation of sounds to a context effect. These authors repeated Smyth and Scholey's experiment, but used a between-subjects paradigm, asking one group of subjects to simply listen to the tones, while another group of subjects pointed to the position of the sound source. Mere listening to sounds presented to the left and right of a subject's head failed to impair memory for the Corsi blocks, prompting Klauer and Stegmaier to argue that disruption of Corsi blocks by left–right judgements is not due to shifts of spatial attention, but that the process involves a decision-making element and therefore relies on the central executive.

We believe that the suggestion that any of the sound-based tasks used in the aforementioned studies may have relied on spatial or central resources may be flawed for two reasons. First, not all sounds are equally easy to localize, and thus by using difficult-to-localize tones as stimuli, Klauer and Stegmaier's (1997) study may have exaggerated the involvement of central processes. Therefore, it is possible that making left–right decisions about tones does indeed rely on the central executive, but that were more localizable broadband sounds used, central executive involvement would be minimal. Second, by using *predictable* locations for auditory stimuli, the above studies fail to establish the interaction between a true sound localization task and memory for spatial information. For instance, if our interpretation of Baddeley and Lieberman's auditory tracking task is correct, it appears that subjects may have simply relied on the pendulum's predictable trajectory for their response, performing a motor tracking task rather than sound localization per se. Similarly, the use of a left–right judgement task (Klauer & Stegmaier, 1997; Smyth & Scholey, 1994) fails to examine the accuracy with which participants actually identified the precise location of sound in space, but may have simply required binary decisions.

In the studies reported below, we have made an attempt to rectify the above issues. In each study, participants were required to identify the location of a series of sounds, but were unaware of the number and position of speakers. In addition, localizable bursts of broadband sound were used instead of tones, and there was no predictable relationship between the location of one sound and that of the next. This set-up ensured a legitimate test of subjects' ability to identify the source of sound, using the timing and intensity cues provided by each noise burst. The effect of phonological, visuospatial, and central working-memory tasks on localization was then tested using a dual-task paradigm. As well as demonstrating the effect of competing tasks on sound localization, this paradigm tested the engagement of each working-memory component in sound localization. All working-memory tasks were presented on a computer screen, and while a spoken response was always required, the nature and timing of this response was determined by the particular working-memory subsystem under investigation. The sound localization task was identical in all experiments and involved making a manual response to indicate the spatial position of sound. Finally, in each of the reported studies, the response demands, procedures used, and number of trials were such as to ultimately allow comparison across studies.

In Experiment 1, an articulation task was introduced to assess the role of the articulatory rehearsal process in sound localization. Here, participants were simply required to read and articulate a series of digits presented on the computer screen. In Experiment 2, participants were asked to read and serially recall the digits, thereby assessing the role of the phonological loop (i.e., articulatory rehearsal process plus phonological store) in auditory localization. In Experiment 3 the role of central resources in sound localization was investigated, by requiring participants to add together successive digits presented on the computer screen. Finally, in Experiment 4 the digits were replaced by a display of coloured squares, in order to examine the role of visuo-spatial resources in auditory localization. For all studies, accuracy in the sound localization and working-memory task (when performed in isolation) was measured, and results obtained from these "single-tasks" were compared with those achieved when participants were required to perform the two tasks as a concurrent "dual-task".

EXPERIMENT 1

All experiments were conducted in a 3.28-m (length) × 2.92-m (width) × 2.60-m (height) room, which was sound treated by covering the walls and ceiling with acoustically absorbent material and the floor with thick carpet and underlay. In addition, for this and subsequent experiments, participants were prescreened with a KC50 Kamplex clinical audiometer, and those with hearing problems were excluded from the study.

Method

Participants

A total of 24 right-handed undergraduate and postgraduate student volunteers (12 male and 12 female, average age 25.1 years) participated in the experiment. All volunteers were students from the University of Leeds, whose incentive for participation in the experiment was the chance to win a £50 prize draw.

Apparatus and materials

The articulation task entailed the presentation of a sequence of digits between 1 and 9, which were presented in the centre of a computer screen. A purpose-written software programme controlled the rate and order of presentation of these digits. Participants' spoken responses were recorded by a standard audio-tape recorder. The sound localization task involved presentation of a 100-ms burst of broadband noise, emitted from one of five Mordaunt Short speakers, mounted on a 235-cm semicircular bar and separated, centre-to-centre, by 15° azimuth, relative to participants' heads. The noise bursts were generated at 74 dB (SPL) by a purpose-built noise generator. Participants were asked to identify the location of the sound source by moving a custom-made 25-cm long, 4-cm wide pointer attached to a potentiometer.

Design and procedure

Participants were seated 70 cm from the computer screen and 214 cm from the speaker bar. Standard instructions were read out by the experimenter. Each experiment consisted of a block of eight single trials (four localization, plus four articulation tasks, counterbalanced across subjects), followed by eight dual-task trials (sound localization and articulation performed concurrently), and completed with a further four single sound localization trials.

For the single-task articulation experiment, participants were simply required to utter each digit as it appeared on the computer screen, and recall of digits was not required. Digits were presented at a rate of one per second (*fast articulation*) on half of the trials, and one every 2 s (*slow articulation*) on the remaining trials. A 10-s gap separated every 7 digits, and each block of trials consisted of a total presentation of 35 digits.

The single-task localization experiment involved response to the burst of broadband noise, emitted from one of five speakers at a rate of one a second (*fast localization*) for half of the trials, and once every 2 s (*slow localization*) on the remaining trials. For each sound burst, participants were required to move the potentiometer pointer towards the direction of the perceived sound and press it down to record their response. A 10-s gap was introduced after five bursts of broadband noise, and each block of trials consisted of a total of 25 localizations.

After the block of eight single trials, participants were required to perform a series of dual-tasks, which consisted of sound localization plus articulation of digits when they appeared on the computer screen. Once again, the localization and articulation tasks were presented once a second, or once every 2 s, resulting in the following four combinations: (1) *synchronous* presentation of sound and digits, at a fast rate of one a second, (2) *synchronous* presentation at a slow rate of one every 2 s; (3) *asynchronous* presentation of stimuli, combining fast localization with slow digit articulation; and (4) *asynchronous* presentation, combining slow localization with fast digit articulation. Each of the four combinations was presented twice to participants, in a counterbalanced order. Following the dual-task phase of the study, participants were required to complete an additional four blocks of single-task localization trials (two at once a second and two at once every 2 s). The absolute angular error from this second series of localization trials was then compared with that of the dual-task trials.

Results

Participants' responses to articulation was 100% accurate both when it was performed alone and in conjunction with sound localization. Therefore, performance of the digit articulation task was not affected by auditory localization.

The effect of articulation on sound localization was analysed using a 2 (speed of localization) × 3 (digit articulation: none, present every second, present every 2 s) repeated measures analyses of variance (ANOVA), on the absolute angular error of localization. Performance of single-task localization at a *fast* rate was compared to fast localization in the dual-task conditions (performed with fast and slow digit articulation). Similarly, accuracy of single-task localization at a slow rate was contrasted with localization performed at a slow rate in the dual-task conditions (with slow and fast digit articulation).

Results showed a significant main effect of speed of localization, $F(1, 23) = 25.16, p < .001$. Single-task localization at a rate of once a second, $M = 6.59$, $SD = 2.01$, was found to be

TABLE 1
The effect of digit articulation on angular error of sound localization

	No DA		*Fast DA*[a]		*Slow DA*[b]	
Localization	*M*	*SD*	*M*	*SD*	*M*	*SD*
Fast	6.88	3.37	6.00	1.76	7.25	2.51*
Slow	6.13	2.71	5.90	2.20	5.43	1.60

DA= Digit articulation.
[a]Once per second.
[b]Once per 2 s.
*Error reliably higher than all other dual-task conditions ($p < .01$).

associated with a higher error rate than that of once every 2 s, $M = 5.76$, $SD = 1.97$. However, the main effect of digit articulation on sound localization was not statistically reliable, $F(2, 46) = 2.13$, $p < .1$. The ANOVA also revealed a significant interaction between speed of localization and articulation, $F(2, 46) = 6.70$, $p < .05$. Post hoc Newman–Keuls' tests of the components of this interaction revealed that the effect of digit articulation on localization performance was confined to when participants were required to localize every second, but articulated digits only every other second (see Table 1). No other comparisons were reliably different.

Discussion

The primary aim of this study was to consider the effect of digit articulation on auditory localization. However, articulation was not found to affect localization accuracy in a uniform manner across the different conditions. When broadband noise was produced at a rate of once every 2 s, participants' performance was similar whether localization was performed in isolation, or concurrently with articulation. These results suggest therefore that the articulatory rehearsal process is not involved in auditory localization. The pattern of results was more complex, however, when localization was required at a rate of once a second. When articulation and localization were performed concurrently and in synchrony at a fast rate, the degree of error in localization was not reliably different from when localization was performed alone and at a fast rate. However, the addition of a concurrent asynchronous articulation task (i.e., at a slow rate) caused a significant disruption to auditory localization. A possible interpretation for these results emerged after a consideration of participants' account of their performance on each task.

According to these accounts, when localization and digit articulation were performed together (at a rate of one a second, or one every 2 s) successful localization was achieved because, with practice, participants developed a rhythm that combined articulation of the digit and moving the potentiometer arrow. Therefore, these conditions required localization and articulation together, either every second or every 2 s.

This rationale is supported by a number of studies that report that simultaneity of stimulus presentation results in a facilitation of dual-task performance, because responses to the two tasks become coordinated. This coordination is thought to result in a more successful use of resources, rather than a competition for these facilities (see Wickens, 1992). Certainly in the most extreme case, the outcome of such coordination is thought to be the performance of the two tasks as a single-task (Klapp, Hill, Tyler, Martin, Jagcinski, & Jones, 1985). Finally, Heuer (1996) states that when tasks are performed concurrently, they rely on the same timing control, and, consequently, performance is impaired if a slow task is paired with a fast task.

While some clarification of our results is provided by the above studies, the fact that a high error rate was not observed when slow localization was combined with the two rates of digit articulation suggests that the pattern of results cannot simply be attributed to whether localization and articulation were in or out of synchrony. Alternatively, the high error in localization observed in the dual-task condition that required fast localization with slow digit articulation may well have been due to an active "switching" between localization and articulation, which was further complicated by an already difficult localization task (as shown in Table 1, error associated with fast localization was higher than that for slow localization).

Thus, it is possible that performance of this particular combination of fast responding to the localization task and slower responding to the articulation task required more involvement of the central executive and not the articulatory rehearsal process. If this explanation is correct, then error in this particular condition should increase systematically with increases in the cognitive load imposed by the working-memory task. Consequently, in addition to exploring the role of each working-memory component in auditory localization, we continued to present the working-memory stimuli and sounds at a "fast" and "slow" rate in all subsequent studies, to examine subjects' performance in this particular dual-task condition.

With respect to this study, since the degree of error in localization was not significantly affected by articulation, we can assume that the articulatory rehearsal process is not involved in identifying the source of a burst of broadband noise. In the next experiment we examined the role of the phonological loop in auditory localization, by requiring the serial recall of articulated digits.

EXPERIMENT 2

Method

Participants

A total of 24 right-handed undergraduate and postgraduate students from the University of Leeds (12 male, 12 female, average age 22.21 years) participated in the experiment. All volunteers were paid for their participation.

Design and procedure

The materials and design were the same as those used in Experiment 1. In this experiment, participants were once again required to articulate the digits presented on the computer screen. In addition, however, they were asked to recall the seven digits aloud in the order in which they had been presented. Recall was required during a 10-s gap, presented between sets of localizations. Once again, for the single-task conditions, digits for serial recall and sounds for localization were presented at two different rates of one a second and one every 2 s. The combination of these continued to result in four dual-task conditions, the order of which was counterbalanced across subjects.

Results

As in Experiment 1, localization performance was assessed using a repeated measures ANOVA. The main effect of the speed of localization was again statistically reliable, $F(1, 23) = 15.41$, $p < .001$, with higher error in the fast condition, $M = 8.28$, $SD = 2.46$, than in the slower condition ($M = 6.46$, $SD = 1.97$). The effect of serial recall was also reliable, $F(2, 46) = 8.05$, $p < .001$, the disruption being greatest following digit presentation at a rate of one every 2 seconds. The ANOVA did not reveal a reliable interaction between rate of digit presentation and speed of localization, $F(2, 46) = 2.13$, $p > .1$. However, since our hypothesis predicted that error would be high in the condition which required subjects to articulate digits at a fast rate whilst localizing at a slow rate, we conducted a planned comparison between the error in this condition and single-task localization performed at a fast rate. Results revealed a reliable difference in mean angular error, $t(23) = -3.77$, $p < .01$. No other planned comparisons were reliable (see Table 2).

We also examined the effect of concurrent auditory localization on serial recall performance, by computing the number of digits recalled in the correct order and correct position, and we once again analysed the results using a 2 (rate of digit presentation) × 3 (localization: none, present every second, present every 2 s) repeated measures ANOVA. The effect of localization was found to be highly reliable, $F(2, 46) = 21.71$, $p < .001$, but accuracy in serial recall was not influenced by the rate of digit presentation, $F(1, 23) = 0.100$, $p > .1$. Post hoc comparisons revealed that requiring concurrent localization interfered with serial recall ($p < .001$), but within the dual-tasks, the magnitude of interference by the two speeds of localization was not significantly different. An interaction between localization and rate of digit presentation was also observed, $F(2, 46) = 14.02$, $p < .001$. As illustrated in Figure 1, within the four dual-task conditions, serial recall proved to be significantly more accurate when the two tasks were performed in synchrony. From the seven digits, an average of 3.8 ($SD = 1.7$) were correctly recalled in the fast synchronous condition, and a mean of 4.1 ($SD = 1.5$) in the slow synchronous condition. The greatest decrement in serial recall was found to be when fast localization was combined with slow digit articulation ($M = 3.0$, $SD = 1.6$), but there was also an evident increase in error when rapidly presented digits for serial recall were articulated during performance of the slow sound localization task ($M = 3.3$, $SD = 1.9$).

TABLE 2
The effect of concurrent serial recall on angular error of localization

	No SR		*Fast SR*[a]		*Slow SR*[b]	
Localization	*M*	*SD*	*M*	*SD*	*M*	*SD*
Fast	7.40	3.39	7.89	2.46	9.56	3.07*
Slow	6.08	2.27	6.55	2.41	6.76	2.74

SR = Serial recall.
[a]Once per second.
[b]Once per 2 s.
*Reliably different from error in single-task fast localization ($p < .01$).

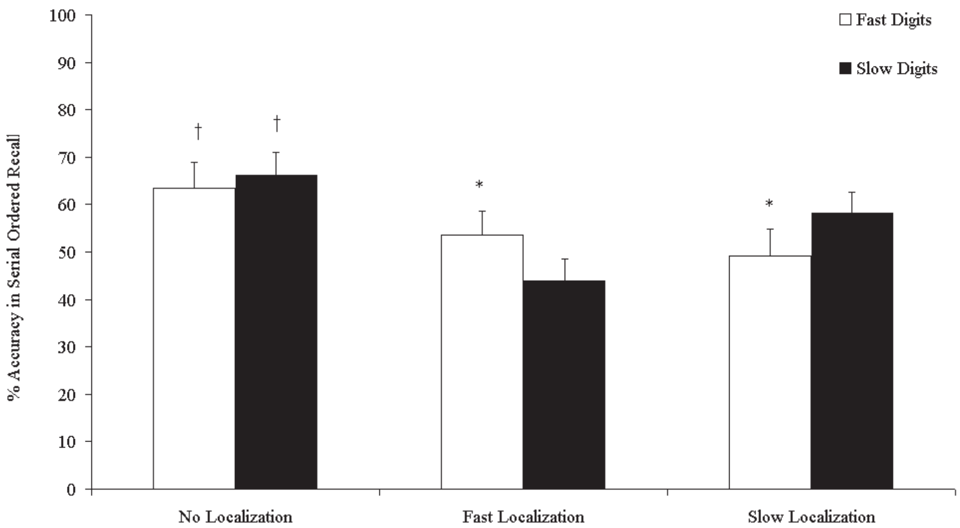

Figure 1. The effect of concurrent localization on serial recall of digits (mean percentage accuracy and standard deviations). *Reliable difference between fast and slow digit presentation ($p < .01$). †Performance reliably better than all dual-task conditions ($p < .01$).

Discussion

As in the previous experiment, localization performance was not impaired in three out of the four dual-task conditions. Specifically, compared to the single-task trials, a high error in localization was again confined to one particular dual-task condition, when fast localization and slow digit articulation were combined. Therefore, these results give further support to the suggestion that this particular combination of tasks may have placed some demand on central resources, since participants were required to alternate their response between localization and articulation of digits for serial recall.

With respect to serial recall, a greater number of digits were remembered when this task was performed alone than when it was attempted with concurrent auditory localization. In addition, within the dual-task conditions, serial recall was more accurate when digits and sound were presented at the same speed, but significantly fewer numbers were remembered when difference in presentation rate of stimuli meant that participants had to switch between localization and digit articulation. This general impairment of serial recall by auditory localization may suggest that the phonological loop component of working-memory is somehow involved in auditory localization. However, this account may be somewhat problematic, since a reciprocal impairment of sound localization by articulation of digits for serial recall was not observed in this experiment.

While serial digit recall is classically regarded as a test of short-term memory capacity, the requirement to ensure that digit order is correctly reproduced has also been suggested by some to require a degree of central processing, especially where a participant's maximum span is approached (e.g., Baddeley et al., 1998; Groeger, 1997; Groeger, Field, & Hammond, 1999). With respect to the above experiment, demand for central resources would be greater still, considering participants had to control their articulation, encoding and rehearsal of digits for serial recall, whilst also selecting a response for the sound localization task. The combination of such demands on a limited-capacity central resource may have been less detrimental to sound localization, since response to this task was discrete and immediate. However, it is clear that such high processing demands during encoding and rehearsal of digits impaired participants' subsequent recall.

To summarize, results of the first two experiments in this report do not support a role for the phonological loop component of working-memory in auditory localization, since accuracy in localization was not impaired by concurrent performance of two tasks that are classically thought to rely on the phonological component. Difficulties in localization for one particular dual-task combination were linked to a high demand for central resources, namely when participants were required to alternate between localization of sound presented at a fast rate and articulation of digits presented at a slower rate. Thus, in order to clarify some of the issues related to task switching, and in an attempt to explore the attention-demanding and decision-making aspects of sound localization, in the next experiment, we specifically examined the role of central resources in auditory localization.

Previous studies have suggested that due to its attentional and information-processing characteristics, the auditory version of the Paced Visual Serial Addition Test (PVSAT) relies on central resources (Channon, Baker, & Robertson, 1993; O'Donnell, MacGregor, Dabrowski, Oestreicher, & Romero, 1994). We predicted that if the central executive is involved in auditory localization, then a general reduction in localization accuracy would be observed, when performed concurrently with PVSAT, and that the serial addition test itself would be disrupted by concurrent localization. Furthermore, we assumed that this general impairment of localization for all dual-task conditions would conceal the high error observed in the "switching" condition of previous studies, where the requirement to localize was faster than digit presentation.

EXPERIMENT 3

Method

Participants

A total of 24 right-handed volunteers (12 male, 12 female, average age 26.25 years) from the University of Leeds were paid to participate in these experiments.

Design and procedure

The materials, design, and rate of stimulus presentation were identical to those described in Experiments 1 and 2. In this experiment, however, participants were required to add sequential pairs of the digits as they appeared on the screen. For instance, the correct response to the series of digits: "3, 6, 2, 8, 1, 9, 7", was: "9, 8, 10, 9, 10, and 16". As with previous experiments, five sets of seven digits were presented in the dual-task condition, with a 10-s pause introduced after every seven digits.

Results

Localization performance was examined using a 2 × 3 repeated measures ANOVA. As before, an effect of speed of localization was observed, $F(1, 23) = 544.81$, $p < .001$, and again as before,

TABLE 3
The effect of concurrent PVSAT on angular error of localization

	No PVSAT		*Fast PVSAT*[a]		*Slow PVSAT*[b]	
Localization	*M*	*SD*	*M*	*SD*	*M*	*SD*
Fast	6.95	2.82	9.42	4.10*	10.10	3.80*
Slow	6.18	2.33	7.64	3.64*†	6.87	2.93†

PVSAT - Paced Visual Serial Addition Test.
[a]Once per second.
[b]Once per 2 s.
*Reliably less accurate than corresponding single-task condition (p < .01).
†Significantly more accurate than fast localization.

greater error in performance occurred when localization was required every second. The main effect of concurrent serial addition was also reliable, $F(2, 46) = 11.16$, $p < .001$. In addition, these main effects were subject to an interaction, $F(2, 46) = 8.40$, $p < .001$. Post hoc Newman–Keuls tests revealed that the greatest localization error occurred when fast localization was performed with slow serial addition of digits. However, unlike Experiments 1 and 2, here, a significant reduction in localization accuracy was found across all dual-task conditions, when compared with single-task performance (Table 3).

Performance on the serial addition task was also analysed, using a 2 (rate of digit presentation) × 3 (localization, none, present every second, every 2 s) repeated measures ANOVA. This revealed significant main effects of rate of digit presentation, $F(1, 23) = 135.03$, $p < .001$, and rate of localization, $F(2, 46) = 75.69$, $p < .001$. Participants' performance of PVSAT was significantly better when digits were presented at a slower pace of every 2 s, and

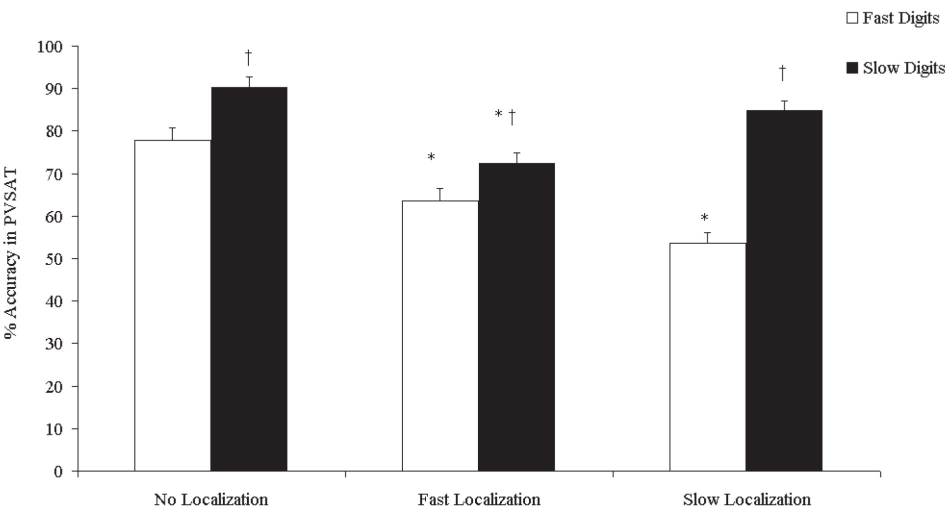

Figure 2. The effect of localization speed on mean percentage accuracy of the PVSAT (error bars depict standard deviations). *Significantly less accurate than corresponding single-task condition (p < .01). †Reliably better performance when compared to fast digit presentation for PVSAT (p < .01).

PVSAT performance was worse when performed concurrently with localization. Results also revealed a significant interaction between localization and performance of PVSAT, $F(2, 46) = 59.68$, $p < .001$, as illustrated in Figure 2. Post hoc tests revealed that for all but the dual-task condition in which localization at a slow rate was paired with slow digit presentation, performance deteriorated with respect to single-task PVSAT. Also, serial addition was always worse when localization was required every second than when it was required once every 2 s.

Discussion

In this experiment, precision in auditory localization was considerably diminished by a concurrent digit addition task. Although the highest error in localization continued to be in the condition where fast sounds for auditory localization were coupled with slow digit presentation, concurrent digit addition also impaired localization in other dual-task conditions. Similarly, the necessity to localize sound impaired concurrent serial addition in three of the four dual-task trials. This impairment of the two tasks suggests that they must rely on the same working-memory resource. Since the performance of PVSAT has been shown to engage central resources in working-memory (Channon et al., 1993; O'Donnell et al., 1994), the results suggest that auditory localization must also rely on central resources. Therefore, following the use of a more rigorous test of auditory localization, our findings strengthen the suggestion that due to its decision-making characteristics, sound localization requires the engagement of central resources (e.g., Abel & Banerjee, 1996; Klauer & Stegmaier, 1997).

However, Klauer and Stegmaier (1977) have also rejected the proposal that identifying the position of sound involves a spatial element (as proposed by Smyth & Scholey, 1994). As outlined in the Introduction, this may have been because Klauer and Stegmaier (and others using sound as a spatial task in studies of working-memory), relied on the use of tones as auditory stimuli, which provide minimal spatial information. In addition, attempting a binary decision with respect to laterally placed speakers (Klauer & Stegmaier, 1997; Smyth & Scholey, 1994) involves minimal use of spatial resources. Therefore, to further examine these issues, in our final experiment we investigated the effect of a visuo-spatial task on auditory localization of broadband sounds, the source of which was not apparent to subjects.

In an attempt to test the engagement of visual and spatial components of working-memory in isolation, we selected a task devised by Logie and Marchetti (1991) which is thought to rely on spatial working-memory resources. The use of this task was particularly valuable since it entailed the sequential presentation of stimuli on the computer screen and required a verbal response from subjects, therefore preserving the general format of previous experiments. However, since this verbal response was not required during the sound localization task, participants were no longer required to switch between response to the sound and that for the spatial working-memory task. We assumed therefore that the high error in localization observed in conditions that required response to sound at one a second and the working-memory task at one every 2 s would not occur in this experiment.

EXPERIMENT 4

Method

Participants

A total of 24 right-handed students were recruited from around the University of Leeds (average age 23.83 years). These 12 males and 12 females were awarded with a cash incentive at the end of the experiment.

Design and procedure

The material and design used for single-task sound localization were identical to those employed in previous experiments, and participants responded using the potentiometer. The spatial working-memory task entailed the sequential presentation of six 24-mm × 24-mm squares, which formed a 2 × 3 array on the computer screen. Each of these squares, which were either the same shade of blue or the same shade of green, were presented either at a fast rate of one a second or at a slow rate of one every 2 s and remained on the screen until all squares were present. One second after presentation of the last square, the screen was cleared, and after a 10-s delay the six squares were re-presented, but order of presentation of two of the squares was altered on 50% of the trials. Participants were required to say whether the two presentation orders were different. Once this task and the sound localization task had been performed alone, participants were required to perform the two together. In this dual-task condition, subjects heard and localized sound whilst observing the first presentation of the six squares, and their response to the spatial working-memory task was required following the second display of the squares, which was presented after the 10-s delay. As with previous experiments, four dual-task conditions were presented, and the order of presentation was counterbalanced across participants.

Results

In this experiment, accuracy of localization was not reliably affected by the rate of presentation of broadband noise, $F(1, 23) = 3.53$, $p > .1$. Sound localization was impaired by concurrent performance of the spatial task, $F(2, 46) = 15.42$, $p < .001$, but post hoc Newman–Keuls analyses revealed that both rates of spatial stimulus presentation resulted in a similar degree of impairment in localization performance. With respect to accuracy of localization performance, the interaction between rate of auditory localization and rate of presentation of the spatial stimuli approached significance, $F(2, 46) = 3.07$, $p = .056$; see Table 4. Post hoc comparisons revealed that subjects were more accurate in identifying the location of sound when it was presented at a slow rate, for all three conditions of spatial stimulus presentation ($p < .05$).

Performance on the spatial task was not affected by the rate of presentation of the spatial stimuli, $F(1, 23) = 1.28$, $p < .1$. However, this task was impaired by concurrent sound localization, $F(2, 46) = 166.02$, $p < .001$. Post hoc Newman–Keuls tests revealed that within the dual-task conditions, performance was more impaired when fast localization was required. The ANOVA also revealed a reliable interaction between speed of delivery of the spatial stimuli and the rate at which localization was required, $F(2, 46) = 8.71$, $p < .001$; see Figure 3. Further Newman Keuls' analyses showed that in the absence of localization, performance on the spatial task was better when the stimuli were presented at a slow rate. During the dual-tasks, when localization was at a fast rate, performance on the spatial task was the same whether the squares were presented at a fast or a slow rate. However, when concurrent localization was

TABLE 4
The effect of concurrent spatial working-memory task on auditory localization

	No SWM		*Fast SWM*[a]		*Slow SWM*[b]	
Localization	*M*	*SD*	*M*	*SD*	*M*	*SD*
Fast	8.13	5.21	10.52	6.73*	10.18	6.55*
Slow	6.62	1.97	7.68	2.65*	7.90	2.29*

SWM = Spatial working-memory.
[a]Once per second.
[b]Once per 2 s.
* Reliably different from error in single-task condition ($p < .01$).

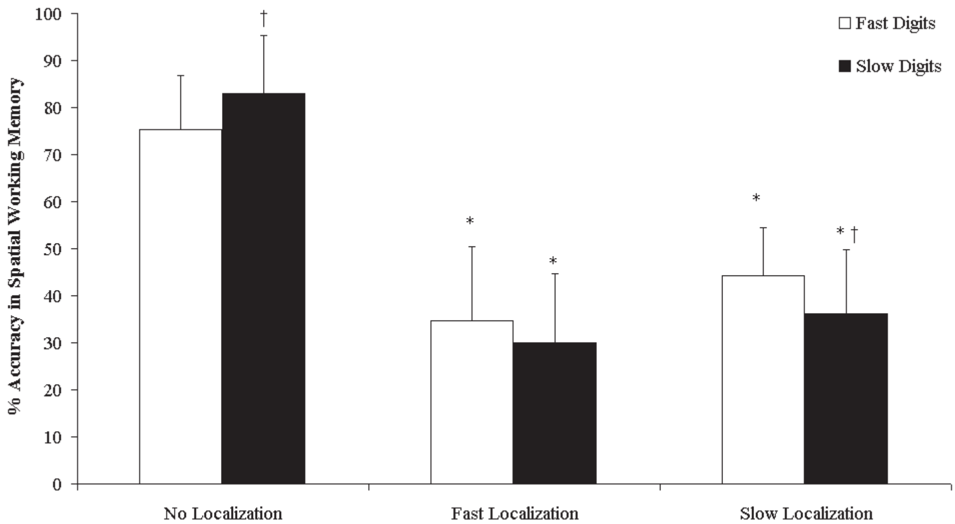

Figure 3. The effect of localization speed on mean percentage accuracy of the spatial working-memory task (error bars depict standard deviations). *Reliably different from corresponding single-task condition ($p < .05$). †Reliable difference between fast and slow spatial task ($p < .05$).

slow, participants were less accurate at the spatial task when the squares were also presented at a slow rate ($p < .05$).

Discussion

In this experiment, the spatial working-memory task and auditory localization were both significantly impaired when participants were required to perform the two tasks together, suggesting that both tasks rely on the same working-memory resources. As predicted, an unusually high decrement in sound localization was no longer observed during the asynchronous dual-task condition, when fast sounds for localization were paired with slow presentation of the squares. In this experiment, subjects were no longer required to alternate between moving the potentiometer arrow and providing a verbal response during the asynchronous condition, reducing the requirement for extra central resources in this asynchronous condition and making it similar to the synchronous condition.

Participants' performance on the spatial working-memory task was found to be better when stimuli were presented at a slow rate in the single-task condition, but under dual-task conditions, this pattern was reversed. Since the time elapsed between presentation of the first square and response to the spatial memory task was longer when stimuli were presented at a slow rate, participants had more of an opportunity to rehearse the to-be-remembered material in the slow single-task trials. However, in the dual-task conditions, the requirement to localize sound would presumably reduce this opportunity for rehearsal, enforcing a higher reliance on recency, and thus allowing better performance for shorter dual-task trials.

In conclusion, this study points to the possibility that auditory localization requires not only central processing, as implied by results of the earlier studies reported above, but also some aspects of spatial memory.[1] In the final set of results presented below we aimed to establish whether central or spatial resources are more functional during localization performance.

COMPARISON ACROSS STUDIES

For each of the four studies reported above, participants completed a series of identical single-task auditory localization experiments, both prior to and following the dual-task condition. This baseline performance of each of the groups taking part in each study did not differ reliably, $F(3, 91) = 1.0, p > .1$. Those taking part were therefore similar, not only in age and educational background, but also in ability to perform the localization task. Consequently, this allowed us to legitimately compare the decrement caused by different types of concurrent working-memory task. To do so, we calculated an "index of decrement" for localization in each dual-task condition (for each of the participants in all four studies), by expressing that individual's error in dual-task localization as a proportion of his or her performance in the comparable single-task. Therefore, an impairment of the task in the dual-task condition (compared to single-task performance) would produce an index higher than 1 (see Figure 4).[2] This calculation produced normally distributed, standardized units of decrement, which were submitted to a three-factor ANOVA, with one between-participant factor (study) and the within-participant factors of rate of sound presentation (2) and rate of working-memory task presentation (2).

Results revealed a significant effect of study, $F(3, 91) = 5.05, p < .005$. Two planned comparisons revealed that PVSAT was associated with reliably more decrement than any other secondary task ($p < .05$), while the decrement associated with the spatial task was only reliably higher than that of the articulation task ($p < .05$). Thus, these cross study contrasts suggest that the primary deficit caused by concurrent task performance arises through increased

[1]We also assessed the accuracy in auditory localization during concurrent performance on the "visual" version of the task devised by Logie and Marchetti (1991). Results did not show an impairment of either sound localization or visual working-memory when performed concurrently.

[2]Single- and dual-task localization values were also standardized using z scores. An index of decrement was calculated using the z-scored values, which were then subjected to the same analyses of variance. The pattern of results were identical to those described below.

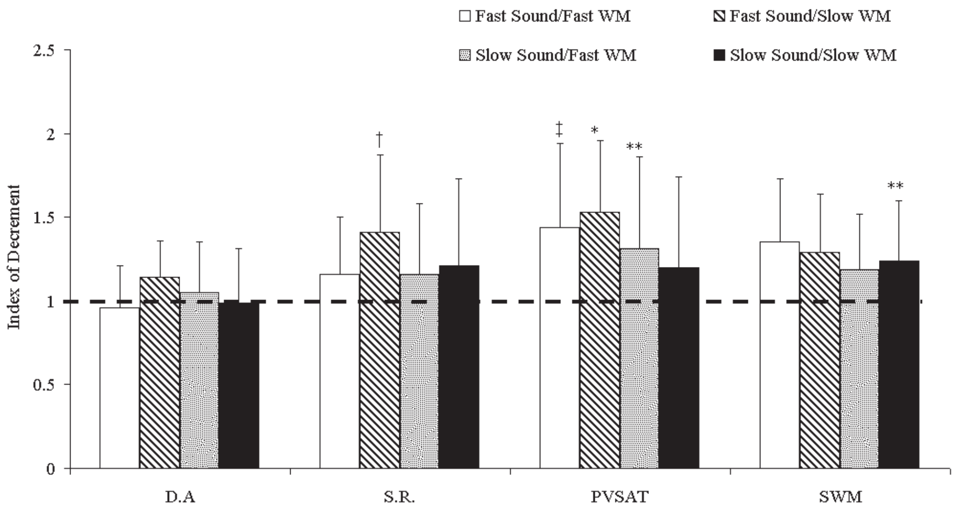

Figure 4. Mean index of decrement for all dual-task conditions across the four experiments (error bars depict standard deviations). Dotted line represents single-task performance. DA = Digit articulation, SR = Serial recall, PVSAT = Paced visual serial addition test, SWM - Spatial working-memory, WM = working-memory task. ‡Decrement higher than SR and DA ($p < .05$). *Index reliably higher than DA ($p < 0.01$). †Value higher than DA ($p < .01$). **Decrement higher than DA ($p < .05$).

requirement for central resources. The analysis also revealed a main effect of rate of localization performance, $F(1, 91) = 13.14$, $p < .001$, such that performance at a fast rate suffered more in the dual-task conditions, than did performance at the slower rate. The main effect of rate of working-memory stimulus presentation was not reliable, $F(1, 91) = 2.65$, $p > .1$, but was subject to an interaction where a slow rate of digit presentation resulted in better localization performance during the digit articulation and serial recall studies, $F(3, 91) = 3.96$, $p < .05$. Finally, a three-way interaction, involving study and rate of presentation for the working-memory and localization tasks, was also observed, $F(3, 91) = 4.46$, $p < .05$.

Results illustrate that across the four studies, localization performance was better under articulation, irrespective of the dual-task condition. The particularly high decrement associated with the "switching" condition is shown to increase steadily across the first three studies. Therefore, as predicted, the requirement to alternate between articulation of digits and moving the pointer was more disruptive to localization as demand for central resources steadily increased. Although all dual-task conditions (except digit articulation) show clear decrements in performance when localization decisions were made every second, it is only in the task that demanded central resources (i.e., PVSAT), and then only when digits were also presented rapidly, that performance truly suffered. Clearly, the results of these cross-study analyses illustrate that while a decrement in localization is most prominent when paired with a centrally demanding serial addition task, this decrement is never reliably different from that imposed by the spatial working-memory task. Therefore, while a role for central resources in auditory localization is confirmed by the above data, further work is required to verify the role of spatial resources in auditory localization.

GENERAL DISCUSSION

A number of important results emerged from the studies reported above. First, a series of tasks that engage different components of working-memory were shown to impair individuals' performance in localization of broadband noise. In addition, localizing broadband noise interfered with the ability to use particular working-memory resources. Results revealed that localization may be particularly dependent on central and, more equivocally, on spatial resources.

Second, coordinating response to a difficult task performed rapidly, with another task performed more slowly, is shown to produce more error than concurrently performing both tasks at the same speed. At first glance this finding appears to conflict with theories of attention and resource allocation that suggest that some minimum temporal separation is required between responses to concurrent tasks (e.g., Psychological Refractory Period, PRP, see Pashler, 1998). However, while the studies reported here required concurrent performance of tasks, response competition was avoided by separating responses in terms of modality (i.e., spoken and manual). Furthermore, PRP effects are much less obvious where error rather than latency is used as the dependent variable. However, the fact that we would not necessarily expect to observe PRP effects does not itself explain why performance was better when presentations were simultaneous. One possibility is that the temporal separation encouraged switching between tasks, with a concomitant reduction in performance, while simultaneous presentation encouraged task integration. The "switching" issue is discussed further below, and it is noteworthy, in relation to the task integration possibility, that several studies report performance enhancement when tasks are combined. For example, Frensch, Buchner, and Lin (1994) found that when a sequence learning serial reaction time task was performed with a tone-counting task, impairment of the serial reaction time task was weaker when stimuli for the two tasks were presented simultaneously than when a delay was introduced between the two stimuli (see Schmidtke & Heuer, 1997, for further examples of task integration).

We suggest that the high error observed when fast sound localization was performed with slow digit presentation (Experiments 1–3), is associated with the effort involved in an active "switching" between response to the two tasks—a feature that is likely to be coordinated by the central executive (see Baddeley et al., 1998). Interference in the sound localization task was higher during this condition than when the two tasks were performed together at a fast rate, probably due to the adoption of a more successful strategy by subjects in the latter condition. In other words, instead of switching between the two tasks, we believe that in the latter condition, subjects combined their response to the two tasks, effectively performing one task. This assumption might also explain why a particularly high error in this condition was mainly observed in the first three experiments, since only in these experiments was an articulation task required *during* sound localization.

In summary, by proposing a role for the central executive in auditory localization, we concur with the study reported by Klauer and Stegmaier (1997). However, since their research required decisions about the source of tones, which are known to be difficult to localize, it is possible that their results may have exaggerated the requirement for central processing in localization tasks. Our results confirm this requirement even with easily localizable sounds.

The contrast across studies demonstrates clearly that imposing additional requirements on the central executive leads to a clear (further) decrement in performance. This cross-study comparison also reduces the impact of another potentially confounding variable; the requirement that manual responding may impose on the visuo-spatial sketch pad. Since the response requirements were identical in each study, the decrement in localization performance across studies seems clearly due to an increase in requirements for central processing resources, rather than demands placed on the slave systems. This is not to suggest that the VSSP is not involved in sound localization, merely that the present studies do not show a separate contribution from visuo-spatial interference, although it is also possible that the reduced ability to perform Logie and Marchetti's (1991) spatial task when concurrently localizing sound stems from some dependence that the spatial task may itself have on the Central Executive (see Quinn & Ralston, 1986; Salway & Logie, 1995). At present, however, until this matter is resolved by further research, we wish to leave open the possibility that Smyth and Scholey (1994), who suggest that localization depends on spatial processing, may also be partly correct.

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Original manuscript received 21 December 2001
Accepted revision received 25 June 2002