Attentional demands of perception of passive self-motion in darkness

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Abstract

The purpose of this study was to determine whether significant attentional resources are required to accurately monitor changes in bodily orientation, using vestibular information. This question was addressed firstly using a dual-task paradigm in which orientation perception tasks and a speeded auditory tone discrimination task were carried out either singly or in combination. For the active orientation perception task, subjects were seated in darkness on a motorised chair which could be rotated about an earth-vertical axis. Following passive angular displacements, subjects were required to return the chair to their perceived starting position, using a joystick which controlled chair motion. For the speeded auditory task, subjects pushed a hand-held button as fast as possible when a tone was presented over headphones. When the two tasks were combined, reaction times on the auditory task increased. Reaction time also increased when subjects were simply asked to fixate during rotation. A second experiment demonstrated that if attention was occupied by performance of a demanding mental arithmetic task during the passive rotation, accuracy of subsequently repositioning the chair to the origin declined, implying that change in orientation had been less accurately registered when performing the concurrent mental task. In combination, these findings indicate that a small but significant degree of attention or cognitive effort is necessary to monitor accurately the direction and amplitude of a brief angular rotation, and to suppress vestibulo-ocular reflex eye movement. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In our daily activities, we combine visual, somatosensory and vestibular information to monitor our orientation and self-motion relative to the environment. However, if visual information is unavailable normal subjects are still able to navigate with considerable success [25], and judgements of position and movement remain quite good even when subjects are also deprived of somatosensory information and must rely solely on vestibular input [4,9,43]. It is possible that the utilisation of non-visual sensory input to perceive and control orientation and self-motion is a relatively automatic process, and requires no cognitive effort. However, there is now accumulating evidence from neuroimaging studies and findings in neurological patients suggesting active cortical processing of vestibular information concerning orientation [8,14,17,19,32,42].

Whereas the sensory characteristics of the vestibular system are well understood, and the cognitive processing involved in visuo-spatial perception has been extensively researched, there has been little investigation of the cognitive processing of vestibular information in healthy human subjects. It is probable that many different cortical structures contribute to the various modes of processing required for differing orien-
tation tasks. For example, research into the diverse manifestations of ‘spatial neglect’ caused by cortical lesions (especially of the right posterior parietal cortex) indicates that processing of cognitive spatial representations of object orientations or relative locations and visual-manual coordination in near space may be dissociated from processing of self-orientation with respect to other reference frames, such as geometric space or the environment [5,40]. Dual task techniques provide a useful means of clarifying the central processing involved in vestibular-based perception of orientation. Various orientation tasks can be systematically combined with concurrent mental tasks which differ in terms of the nature of the cognitive processing that they require. Combinations of orientation and mental tasks which result in a decrement in performance on either task (relative to single task performance) can then be assumed to compete for processing capacity. The extent to which each task makes demands on general processing capacity can be studied by varying task difficulty, while demands on specific cognitive resources are identified by demonstrating ‘selective’ interference between certain types of task (e.g. visuo-spatial or verbal).

Using dual-task studies, selective interference has been found between performance of visuo-spatial mental tasks and various active orientation tasks, including pursuit eye movements [2], tracking a moving auditory target with a pointer [3], and intentional hand movements [31,34]. A number of experiments have also demonstrated interference between performance of visuo-spatial mental tasks and postural control [1,20,27,44], and between non-spatial reaction time or mental arithmetic tasks and postural control [10,22,35,38]. Indeed, simply counting backwards has been shown to disrupt the ability to accurately monitor or control self-orientation relative to the environment when walking without vision [6,33,37].

In all these previous studies of interference between mental activity and orientation, the orientation task employed has involved initiation and control of motor activity, whether eye or hand movement, postural sway, or locomotion. Consequently, they do not constitute a test of whether attention is required for the perception of orientation, since the interference observed might have been between mental activity and motor control. Moreover, both vestibular and somatosensory information was available in the studies which used whole body orientation tasks, and so it is impossible to isolate any effects of processing vestibular information per se on mental task performance. The aim of the present study was therefore to determine whether cognitive processing is required for the perception of brief angular motion, using only vestibular information.

We employed an orientation task in which subjects were rotated in a motorised chair and then used a joystick to return themselves to their initial position [9]. It has been suggested that this task could be accomplished with little or no requirement for attention or cognitive processing during the passive rotation, if the change in orientation is simply registered at the level of the brainstem and cerebellum [41]. If this is the case, subjects’ performance on a concurrent mental task should be unaffected by the need to monitor the passive turn (in order to subsequently reposition themselves accurately). Consequently, the attentional demands of perception of orientation were evaluated in our first experiment by determining the effect of monitoring passive rotation on reaction times on a concurrent auditory task. As a more direct demonstration that perception of passive motion is impaired by competing attentional demands, we then examined the effect on accuracy of repositioning of performing a demanding, continuous mental task (backwards counting) during the passive turn.

2. Experiment 1

In this experiment, we examined the effects on reaction times of three ‘active’ orientation conditions. The first active condition was a simple repositioning task, in which subjects were smoothly rotated up to 170° in a motorised chair and then used a joystick to return themselves to their initial position as accurately as possible. We also employed a more complex repositioning task, in which subjects were asked to reposition themselves following turns of equivalent amplitude to those employed in the simple turn condition, but with an uneven velocity profile. The purpose of this manipulation was to investigate whether perception of such complex motions requires more central processing (hence inducing greater interference in the performance of the auditory task) than perception of smooth angular motion. This hypothesis was prompted by the finding by Berthoz et al. [4] that subjects were able to accurately reposition themselves following a simple linear displacement but were unable to accomplish this task when the displacement had a complex velocity profile. They suggested that the velocity profile may be used to monitor change of orientation in space, and their results suggest that a complex velocity profile makes this task more difficult. In our third active orientation condition, subjects were not asked to monitor their orientation, but instead fixated an LED during the turn. Our aim was to investigate whether suppression of vestibular-based reflex eye movements could be achieved automatically, without cognitive effort. This provided an active orientation condition which could be compared with the repositioning task, which requires subjects to consciously register and
retain in memory a record of their change in orientation.

For comparison with these three ‘active’ orientation conditions, two control conditions were employed. The first consisted of performance of the reaction time task while seated in a stationary chair, while the second was an ‘unattended movement’ condition, in which subjects were rotated one turn but were instructed that they would not be asked subsequently to reposition the chair, and hence did not need to monitor their change in orientation. The purpose of the second control condition was to determine whether even unattended vestibular input had an effect on reaction time—for example, by distracting subjects from the auditory task.

2.1. Methods

2.1.1. Subjects

The subjects were sixteen healthy adults with an age range of 22–38.

2.1.2. Design

Subjects performed the auditory task under three dual task conditions: ‘simple motion’, ‘complex motion’, and ‘fixation’. Two baseline measures of auditory task performance were obtained, one while the chair was stationary, and one while the subject was exposed to chair movement with no requirement to fixate or reposition the chair (the ‘unattended motion’ condition). To provide baseline comparisons for performance on the orientation tasks, the ‘simple motion’ and ‘complex motion’ repositioning tasks were also carried out without concurrent performance of the auditory task. There were twelve consecutive trials in each condition, and the order of conditions was counterbalanced.

2.2. Apparatus and procedure

2.2.1. Orientation tasks

Testing took place in a completely darkened room, with the subject seated on a motorised chair which could be smoothly rotated about an earth-vertical axis. During rotations, the subject’s head was maintained by a head rest in an upright position and centred on the axis of rotation. White noise was presented by headphones in order to mask ambient sounds which might provide an auditory cue to orientation. Perception of self-motion during such rotations must be mediated almost exclusively via the semicircular canals, since bilaterally labyrinthine defective subjects are unable to estimate the extent or direction of their rotations [9].

The stimuli consisted of six different rotations in the clockwise (CW) direction, and six in the counterclockwise (CCW) direction. Each of the six stimuli selected for both directions came from one of six magnitude steps averaging 45, 70, 95, 120, 145 and 170°. In order to minimise learning effects, deviations of $-5^\circ$ or $+5^\circ$ were randomly superimposed on these stimuli, with the constraint that, for a given condition and direction of movement, the deviations for the 45, 70 and 95° steps, and those for the 120, 145 and 170° steps, summed to zero. The order in which the 12 stimuli were presented was randomly determined, with the constraint that no more than two consecutive trials should involve displacements in the same direction. Each displacement had a raised cosine velocity profile (peak $= 50^\circ/s$), and the durations of the stimuli ranged from 2 to 7 s. In the ‘complex motion’ condition the rotational stimuli were modified by superimposing a rippled velocity profile formed by the addition of a raised cosine carrier wave (peak $= 50^\circ/s$) and sine wave modulation with a fre-
frequency ten times that of the carrier wave, and an amplitude 11% of that of the carrier (see Fig. 1).

Following rotation, subjects repositioned themselves to their perceived starting position as accurately as possible, using a joystick control which delivered a velocity demand to the chair servo (maximum velocity $65^\circ/s$). Subjects were instructed to respond promptly, but were allowed to make corrective adjustments. Subjects were provided with ten practice trials to accustom them to the operation of the joystick before testing commenced. At no point during the practice stage, or during subsequent testing, were subjects given any feedback about the accuracy of their repositioning responses. In the ‘fixation’ condition, the chair was rotated in the same way as in the simple motion condition, but subjects were not required to reposition the chair following rotation, but were instead instructed to fixate an LED fixed to the chair. In the ‘unattended motion’ condition the chair was rotated as in the ‘simple motion’ condition, but subjects were not required to fixate or to reposition the chair when it had stopped moving, and were instructed that they need not attend to the rotations.

2.2.2. Auditory tasks

Subjects were required to make accurate and rapid spatial discrimination responses to lateralised tones at a frequency of 1000 Hz, and of 500 ms duration. The interval between a response (or the termination of an opportunity to respond) and the next stimulus was 800 ms and the timeout period was 1000 ms. A failure to respond was coded for any stimulus for which no response occurred within 2000 ms of stimulus onset.

During each trial, eight auditory stimuli were presented through headphones. Stimuli were controlled and responses recorded by a personal computer, which was connected to the headphones and response box via slip rings on the chair. Subjects held the response box at approximately their midline, and positioned their right thumb on the ‘higher’ response button (i.e. more distal from their bodies) and their left thumb on the ‘lower’ button (more proximal to them). An arbitrary stimulus-response mapping was utilised whereby responses to lateralised tones were made on vertically aligned buttons, so as to prevent automatic processing of the spatial relationship between stimulus and response [21]. Thus half the subjects were required to press the ‘higher’ button in response to tones heard in the left ear and the ‘lower’ button in response to right tones, while the remaining subjects had the reverse mapping. Incorrect button selections or failures to respond resulted in auditory presentation of the word ‘Wrong’.

On dual task trials in which an auditory task was

![Fig. 2. Mean percentage constant error in repositioning (top) and variable error in repositioning (bottom) for the simple and complex motion orientation task conditions performed as a single task (baseline) or in conjunction with the auditory discrimination task (Experiment 1).](image)
combined with an orientation task, the auditory task was always begun first and onset of chair rotation was delayed so that the chair rotation would finish at approximately the same time as the end of the set of eight auditory stimuli. Subjects were instructed to wait until after they had responded to the final tone before releasing the response box and repositioning the chair with the joystick, and so were never required to make reaction time and joystick responses simultaneously.

2.3. Results

2.3.1. Perception of orientation

Mean repositioning responses are given in Table 1, which shows that subjects had a tendency to undershoot the starting position, and that this bias was more marked for rotational stimuli of greater magnitude. Consequently, effects of concurrent auditory task performance on the perception of orientation were examined using error scores calculated as signed percentage values, representing repositioning responses as a proportion of the magnitude of the imposed displacement relative to starting position. The constant error was the mean of these scores across the 12 trials within any experimental condition, and reflected the extent of the systematic tendency to undershoot the starting position. The variable error was the standard deviation around the mean constant error, and reflected consistency of judgments irrespective of this systematic bias.

Fig. 2 displays mean constant error (top) and mean variable error (bottom) for both repositioning conditions as a function of each of the auditory task conditions. When the constant error data were subjected to a two-factor repeated measures ANOVA of the effects of orientation condition (simple vs complex motion) and auditory task demands (baseline vs discrimination task), no significant effect was found for orientation condition \( F < 1 \), auditory task demands \( F(1,15) = 2.01, P = 0.177 \), or their interaction \( F(1,15) = 1.41, P = 0.254 \). Similarly, there was no indication that variable error was affected by orientation condition \( F < 1 \), auditory task demands \( F < 1 \), or their interaction \( F(1,15) = 1.45, P = 0.247 \).

2.3.2. Auditory task performance

Fig. 3 displays the means of subjects’ median reaction times on the discrimination task as a function of orientation condition. It is apparent from this graph that reaction times are slower during concurrent orientation task performance (compared with the no rotation and unattended rotation baseline conditions), and this was confirmed by a one-factor repeated measures ANOVA showing a statistically significant effect of orientation condition on auditory task performance \( F(4,60) = 7.96, P < 0.001 \). This effect was examined further by a set of four pre-planned orthogonal contrasts adjusted by the Bonferroni procedure [16]. The contrast between the three active orientation conditions and the two baseline conditions was significant at the corrected significance level \( t(15) = 4.08, P < 0.012 \). No evidence was found for a difference in reaction time for the two baseline conditions \( t(15) = 1.95 \), or for a difference between the fixation condition and the two repositioning conditions \( t(15) = 1.05 \), or for a difference between the two repositioning conditions \( t(15) = 0.72 \). A non-significant decline in accuracy across conditions was also observed \( F(4,60) = 1.85, P = 0.131 \), with 96.9% correct responses when the chair was stationary, 96.7% with unattended motion, 95.0% and 94.7% with simple and complex motion respectively, and 93.9% with fixation.

2.4. Discussion

Our findings indicate that even a minimal orientation task, such as registering change in orientation or fixating during passive motion, requires some degree of attention and thus leads to a reduction in response speed on a concurrent auditory task. Such dual-task
increment in performance occurs only when both tasks require attention, with the result that a ‘concurrent cost’ is incurred when attention must be divided between them [24,28]. Since the auditory task was carried out while the subject was simply being passively rotated, the interference is unlikely to be due to competition for attentional resources necessary for response preparation, initiation, or production. Moreover, the interference was not due solely to exposure to self-motion, as passive rotation with no requirement to monitor orientation resulted in a much smaller, non-significant degree of interference with auditory task performance.

These findings confirm and extend observations from a previous study in which subjects reported their final position after they had been passively rotated in darkness, using multiple combinations of clockwise and counterclockwise angles up to 180° [43]. Performance in judging final orientation was substantially impaired when subjects were required to count backwards while turning, providing preliminary evidence of interference between mental activity and orientation perception. However, an unusual degree of cognitive processing may have been needed in order to monitor, recall and integrate the complex multiple turns employed in this previous investigation. Moreover, in the earlier study subjects indicated their final orientation by reporting which number they faced on an imaginary clockface, and this mode of reporting orientation may have encouraged the use of cognitive imagery or calculation to monitor orientation. The present study has demonstrated that cognitive processing is required not only for such complex orientation tasks, but also for the vestibular perception of brief angular motion in just one direction.

There was no difference between repositioning accuracy following the simple turns and the turns with uneven velocity profiles, and these two conditions had similar effects on dual task performance. Hence the complexity of the velocity profile of the motion imposed on subjects during their change in orientation did not substantially affect the difficulty of monitoring self-movement. This finding suggests that the initial processing of the vestibular information necessary to determine change in orientation is an automatic process of velocity to position integration which takes place sub-cortically, or involves cortical mechanisms other than those which produce the interference between monitoring orientation and making a speeded discrimination. Similarly, it has been observed that the early analogue sensory processing of visual stimuli does not make demands on the central processing channel employed for perceptual and decisional judgements [13].

Interestingly, the requirement to fixate during motion resulted in an increase in reaction time similar to that produced by the requirement to monitor change in orientation. Although interference between two active motor tasks is commonly observed, the degree of cognitive effort required to simply suppress eye movements might intuitively be supposed to be quite minimal. In a study of interference between eye movement control and an auditory reaction time task, Pashler et al. [30] found that saccades elicited by visual targets produced only minimal disruption of dual task performance. Even voluntarily controlled saccadic eye movements resulted in much less interference with manual reaction times than that produced by simultaneous performance of a vocal task, leading Pashler and colleagues to suggest that eye movement control has some minor, non-specific effects on concurrent mental task performance, but does not make demands on the central attentional bottleneck which typically produces substantial decrements in performance of simultaneous motor tasks. Visual fixation shares many of the pathways of the visual pursuit system and, like pursuit, may involve some degree of visual attention [23,26]. Hence, interference resulting from the requirement to maintain fixation may be due to the attentional rather than the motor control demands of the task, which could explain the similarity in degree of interference to that produced by the purely perceptual task of monitoring change in orientation. A perceptual or attentional basis for interference between eye movement control and concurrent mental task performance is also suggested by the observation that involuntary nystagmus exerts no dual-task interference, whereas visual pursuit disrupts performance on a reaction time task [2], and the finding that fixating a white square or a changing pattern interferes with performance on a spatial memory task, while simply looking at a blank screen does not [39].

3. Experiment 2

Although interference with concurrent tasks is widely regarded as evidence that a primary task requires attention [21,29], it could be argued that the effect on auditory reaction times might be produced by a conscious deployment of attention to monitor orientation. Evidence that the ability to monitor orientation (as assessed by accuracy of subsequent repositioning) was itself impaired when attention was occupied with another task would provide a more direct demonstration that attention is required for monitoring passive rotation. Consequently, in order to maximise the effect of the concurrent task on orientation perception, the simple, intermittent auditory task employed in the first experiment was replaced by backwards counting in multiples of seven. Backwards counting is a continuous, demanding mental task which has previously been
shown to interfere with spatial monitoring while walking in darkness [6,33,37], and following complex combinations of passive rotations [43].

3.1. Methods

3.1.1. Subjects

The subjects were eight healthy volunteers with an age range of 21–31.

3.1.2. Design and procedure

Subjects were required to reposition the chair to their starting-point following passive rotations consisting of (a) a single turn, or (b) two consecutive turns of different magnitudes and direction. The ‘two turn’ condition was included in order to make the orientation task more difficult, and hence more sensitive to the effects of dual task interference. The turns used in the ‘two turn’ condition had the same characteristics as those employed in the ‘one turn’ condition. Combinations of turns were randomly selected (with the constraint that the two turns had a different magnitude and direction) and resulted in ten final displacements relative to the starting position.

In the dual task conditions, subjects were required to carry out a counting task during the passive repositioning, consisting of counting backwards aloud in multiples of seven as fast as possible, starting from a randomly selected number between 200 and 999 supplied by the experimenter. The counting task was begun first, and the onset of the chair rotation was timed so that the chair rotation would finish after 15 seconds of counting. Counting task performance was determined by the number of correct subtractions completed during this fifteen second time period. To assess baseline performance on the orientation tasks, the ‘one turn’ and ‘two turn’ repositioning tasks were also carried out without concurrent performance of the backwards counting task. Baseline performance on the counting task was assessed while the chair was stationary. Twelve consecutive trials were administered for each condition, and the order of test conditions was counterbalanced.

3.2. Results

Fig. 4 shows the mean constant error and mean variable error of repositioning in the baseline and dual task conditions. A two-factor repeated measures ANOVA of the effects of orientation condition (one vs two turns) and task demands (baseline vs counting task) on variable error revealed a significant effect of orientation condition \(F(1,7)=40.47, P < 0.001\), dual task demands \(F(1,7)=22.05, P = 0.002\) and their interaction \(F(1,7)=8.15, P = 0.02\). Paired t-tests confirmed that the mental task had a highly significant effect on repositioning accuracy following one turn \((t(7)=7.01, P < 0.001)\) and following two turns \((t(7)=3.84, P < 0.006)\). There was no effect on constant error of orientation condition \([F < 1]\), dual task demands \([F < 1]\), or their interaction \([F < 1]\).

The dual task conditions also affected backwards counting, as significantly fewer correct subtractions \((t(7)=2.39, P = 0.048)\) were performed under dual task conditions (mean = 3.8, S.D. = 1.1) than during the single task baseline condition (mean = 4.4, S.D. = 1.2).

4. General discussion

The findings from this second experiment confirm that using vestibular information to monitor orientation must require attention, since perception of change in orientation appears to be less accurate when attention is engaged on another demanding task during passive motion. In the previous experiment, simply monitoring the direction and amplitude of a brief angular rotation, or fixating during the turn, was sufficient to produce a consistent increase in reaction time on concurrent auditory tone detection or discrimination tasks. Hence it appears that perception of
change in orientation using vestibular information cannot be considered ‘automatic’, in the conventional sense of requiring no attention or central processing capacity, and therefore causing no interference with concurrent mental activity [21,29].

Clearly, there are many different ways in which vestibular information can be utilised, and further research is needed in order to determine the nature and extent of cognitive processing required for each, and the cortical pathways involved. For example, the processes and structures which mediate awareness of self-motion relative to the environment may differ from those which mediate the processing of orientation information for the purpose of postural control. Nevertheless, recognition of the role of cortical processing in basic orientation perception has significant practical and clinical implications, as it suggests that individual differences in central processing might contribute to the extreme variations in the ability to cope with disorientation and to recover from peripheral vestibular lesions.

Brain lesion and imaging studies suggest that one cortical region likely to be implicated in this processing is the parietal-temporal cortex, since this region apparently subserves vestibular perception [7,8,14,17]. To the extent that conscious perception of change in orientation may necessitate generation, storage and manipulation of a spatial representation, the parietal cortex, prefrontal cortex and hippocampus may also be involved, especially in the right hemisphere [11,12,15,18,42]. A study with particular relevance has been carried out by Israël et al. [17], who found that the ability to perform delayed ‘vestibular-guided’ saccades (i.e. to move the eyes back to a target following a small rotation of the subject and a short delay) was severely affected by prefrontal lesions, and by parietal-temporal lesions and supplementary eye field lesions, but not by posterior parietal cortex lesions. One or more of these structures may well be responsible for the central processing which was disrupted during dual task performance in the present study, although the whole body repositioning task employed in the present study is unlikely to have involved the supplementary eye fields, and might have encouraged a more conscious representation of spatial orientation, hence eliciting activation of the posterior parietal cortex. Another possibility is that while different cortical structures subserve monitoring orientation and responding to tones, interference is caused by a shared common pathway, for example linking the pre-frontal and posterior parietal areas [36]. However, since different orientation tasks are likely to entail differing attentional demands, considerable additional research is necessary in order to begin to clarify the cognitive mechanisms and cortical structures involved in diverse orientation-related activities.

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