



# Do neck-proprioceptive and caloric-vestibular stimulation influence covert visual attention in normals, as they influence visual neglect?

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## Abstract

Neck-proprioceptive and caloric-vestibular stimulation have been shown to ameliorate the spatial bias exhibited by patients suffering from unilateral visual neglect. These interventions might in principle have their effect by biasing covert attention towards the neglected side. If so, the same interventions should also modulate covert attention in neurologically-intact subjects. However, we demonstrate here that neither neck-proprioception (vibration of left neck muscles) nor caloric-vestibular stimulation (injection of iced water into the left ear) affect covert visual attention in healthy individuals. These results from normals may distinguish between different accounts for unilateral neglect in patients. In particular, they argue against explanations of neglect solely in terms of a pathological misperception of body orientation within an otherwise normal neural representation of space. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Patients with unilateral neglect fail to acknowledge, explore, or respond appropriately for stimuli located towards the contralesional side of space [17,60,65]. Such clinical deficits can be seen after various unilateral lesions, particularly to the right hemisphere, but are most common following parietal damage centered on the right supramarginal gyrus and adjacent temporal lobe or, much less frequently, on the right dorsolateral premotor regions [23,54,64,65]. Explanations for neglect have typically invoked a bias towards the ipsilesional side either in spatial attention (i.e. patients pathologically attend to the right), or in high-level spatial representations (e.g. damage to trunk-centric representations of visual space) [15,18,31,40]. Although these are often considered rival explanations, there is now an increasing realization that different components may contribute jointly to the manifestation of neglect [16,35].

Although neglect is usually considered as a high-level disorder, rather than a peripheral sensory loss, a number of peripheral sensory manipulations can nevertheless transiently ameliorate neglect [64]. We focus here on two such manipulations, with the aim of understanding the mechanism for their influence, by testing whether they affect covert spatial attention in normals. The manipulations in question are neck-muscle proprioceptive stimulation [27], and caloric vestibular stimulation [53,55]. We initially concentrate on the former, returning to the latter only after our first experiment.

The use of neck-muscle proprioceptive stimulation grew from research suggesting that body posture, and the consequent position of stimuli relative to certain body parts, can influence visual neglect [25,28]. Neglect in line bisection sometimes improves for stimuli placed on the right of the patient's trunk (e.g. [22]). Bisiach and colleagues [8] reported that the location of stimuli relative to the trunk also influences neglect in a tactile exploration task (removing pegs from an array, which was hidden from direct view). However, in the two latter studies, the position of stimuli relative to the trunk altered the exact movements (with the hand etc.) required to perform the task.

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By contrast, in Karnath et al.'s [28] study, exactly the same left or right eye-movements had to be made in all conditions, while trunk orientation was varied. Saccades to left visual-field targets were faster if the right-parietal patient's trunk was rotated towards the left. This provides clear evidence that changes in body posture can modulate neglect by altering the position of visual targets relative to the trunk. This conclusion was confirmed in a further study [25] that required only perceptual judgements for lateralized visual targets, not spatial motor responses. Thus, stimulus position relative to the trunk can modulate purely perceptual neglect in vision.

Muscle vibration can lead to illusions of postural change in neurologically intact individuals [7,29,59], because the discharge caused by the vibration is coded centrally as the lengthening of the vibrated muscles. Karnath and colleagues [25,29,32,33] found that vibrating left neck-muscles in right-hemisphere neglect patients ameliorated their left neglect in various tasks (copying, cancellation, identifying briefly presented objects). This effect of neck vibration demonstrates that purely afferent inputs about current posture are sufficient to modulate visual neglect.

Various different accounts for this neck-vibration effect can be proposed, in accordance with the different component processes that may be deficient in neglect. For instance, Karnath [31] argued that neglect involves a disturbed transformation of spatial inputs, leading to a pathological 'rotation' of egocentric space representation towards the right in left neglect, which biases the patient's exploratory movements towards that side. On this view, neck vibration (and other modulations of afferent input, such as vestibular stimulation) may affect neglect by compensating for the proposed pathological rotation of spatial coding. In apparent support of this, Karnath et al. [26] recorded exploratory eye movements in neglect patients, and observed that both neck-proprioceptive and vestibular stimulation re-centered their biased field of exploration. Moreover, Karnath et al. [26] also found that ocular search patterns for normal subjects could similarly be deviated towards one side or the other by appropriate neck-proprioceptive or vestibular stimulation.

However, it remains possible that instead of affecting neglect by shifting exploratory behavior in accordance with a shift in the egocentric coding of space, neck-proprioceptive and vestibular stimulation might act instead by shifting covert attention towards the affected side. Indeed, the observed effects on exploration might themselves conceivably be caused by such a covert attentional shift. If neck-muscle stimulation acts in the patients by directly shifting covert attention towards one side, then presumably it should be capable of shifting covert attention in normal subjects also. Here we provide the first experimental test of this hypothesis.

Exploring the effects of neck-muscle (and vestibular) stimulation in normals should not only reveal properties of the normal system, but may also help to distinguish between alternative accounts for neglect.

## 2. Experiment 1

Our first study examined whether afferent signals about head-on-trunk posture can bias the direction of covert visual attention in normals. The experimental manipulation was vibration of left neck muscles. When applied in a darkened room, this manipulation can induce an illusory horizontal movement of stationary lights and an altered perception of the subjective straight ahead [7,29,59]. These illusions persist while the vibration is applied. If normal covert visual attention is biased towards the direction that the subjective straight ahead is shifted during vibration, then an attentional bias should be found to the side of the neck vibration in our experimental condition.<sup>1</sup>

As a control for any non-specific effects (and the associated sound) when vibrating on one side, the subjects' left arm was vibrated instead of the neck during control blocks, which should not cause any postural illusion. Note that this control is exactly like that used by Karnath and colleagues [25,33] in patients with spatial neglect. It was implemented again here to make our manipulations with normals as close as possible to those previously found to be effective for neglect patients.

Our measure of any covert attentional bias towards one side came from a visual 'temporal-order' task, previously shown to be a highly sensitive measure for lateral biases of attention in normals, and also for lateral perceptual biases in patient groups [49,52,57,58]. In this task, one visual event is presented in the left visual field, and this stimulus is subsequently followed by a comparable visual event in the right visual field (or vice-versa), on every trial. The subjects' task is to make an unspeeeded judgement concerning which of these two events appeared first. The short interval between the events is varied from trial to trial, along with which side

<sup>1</sup> Another way to test whether neck postural cues can bias normal attention would be to seat the subjects with their trunk at different sharp angles to their head. However, the experimental demands might be transparent to the subject in this situation (e.g. requiring a sustained deviation of the trunk to one side might encourage subjects to direct their attention strategically to that side). Moreover, if we had required subjects to actually twist their trunk to one side, they might need to maintain this unnatural twisted posture with an intentional motor set, which could itself influence any biases in visual attention if motor programming and attention are closely coupled (as argued by, [43,44,46,47]). Therefore, in order to isolate any influence of purely afferent postural signals on normal attention, we chose to study the influence of neck-muscle vibration for subjects whose trunk did not actually deviate.

leads. When attention is not biased to one side, normal subjects are quite accurate at such temporal-order judgements. Their point of subjective simultaneity — that is, the temporal interval between targets at which neither side is consistently judged as coming first — lies close to true physical simultaneity. In other words, healthy individuals' subjective experience of simultaneity occurs when the two stimuli are presented at exactly the same objective time, appearing concurrently. However, directing covert attention to one side has the effect of speeding up perception of events on that side relative to the other side (such that they gain 'prior-entry' into awareness [61]). As a result, events on the attended side are typically judged to precede those on the unattended side (or those on the contralesional side in patients), unless the latter events lead physically by a substantial amount. Both neglect and extinction patients characteristically require a lead of 200 ms or more by a contralesional event before they will acknowledge that it precedes an ipsilesional event (see [49,52]).

We chose this temporal-order task as our measure of any bias in covert visual attention, for two reasons. First, it provides a particularly pure measure of attentional effects on perception, rather than on the speed of response execution or other motor components. Second, it has previously been shown to be sensitive both to normal covert attention [57,58] and also to visual neglect and extinction [49,52].

We implemented the visual temporal-order task in conjunction with neck-muscle vibration, or arm vibration. If neck vibration shifts normal covert attention towards its side, due to the apparent change in postural information, then a prior-entry advantage should be found for visual events on the side of the stimulation (i.e. in the direction of the associated shift in the subjective straight ahead [7,29]), with targets on this side being judged as appearing sooner than events in the other visual field during the neck vibration.

It is critical to ensure that any such effect is truly due to the direction of covert attention, rather than merely to the direction the eyes are pointing in. During neck-muscle vibration, normal subjects mislocate their subjective straight ahead towards the stimulated side [7,29]. If their eyes were allowed to wander towards this subjective straight ahead, this would confound any test of covert visual attention, as information on one side of space would now fall closer to the fovea. It was therefore critical to monitor central fixation throughout the visual testing, to allow measurement of any truly covert attentional shift. Our aim was thus to determine whether neck vibration can influence covert attention, even when the subject is given a clear central landmark and must maintain fixation on this. Note that previous research with neglect patients has shown that left neck-vibration can still modulate their visual deficit on the contralesional side, even when they maintain fixation on such a central landmark [25].

Finally, in order to verify that neck vibration did indeed cause a proprioceptive illusion throughout the experiment for our normal subjects, the perception of subjective straight ahead was sampled between each block of the visual temporal-order task (by having subjects position a light ahead of them in a darkened chamber). As noted earlier, vibration of the left neck muscles typically causes healthy subjects to place their subjective straight ahead towards the left of their actual head/trunk orientation (and in neglect patients, compensates for their pathological rightward misplacement of the subjective straight ahead). By explicitly measuring the subjective straight ahead in our subjects, we could confirm whether they were experiencing the same proprioceptive illusion that is associated with the ameliorative effects of left neck-vibration in neglect.

## 2.1. Method

### 2.1.1. Subjects

Ten normal subjects were tested. As previously observed in studies of normal subjects [7,29], some subjects fail to show a consistent proprioceptive effect on the subjective straight ahead. Of our sample, two failed to show any illusion at all, and the illusion vanished shortly after stimulation began in two other subjects. These subjects were excluded from further study. Of the remaining six subjects, two were male and four female. Their age ranged from 23 to 28 with a median age of 24. Subjects were paid for their time, and tested during a single 2 h session.

### 2.1.2. Apparatus and materials

Subjects were seated in an opaque, light-bulb shaped cabin with their head at the center of the upper spherical portion (190 cm diameter). Testing took place in complete darkness. Subjects sat upright in a chair and were secured with a four-point seat belt. Their heads were secured with a chin rest. All LEDs were mounted on the interior surface of the cabin. A single yellow fixation LED was directly in front of the subject. Two green LEDs served as lateral targets, each mounted 7.5° to left or right of fixation at a distance of 73 cm. These LEDs were controlled by an IBM compatible laptop. Two buttons were used to register responses. The button to register a 'left target first' response was mounted on the left armrest, and the button for 'right target first' was mounted on the right armrest. Responses were made in an unsped fashion at the end of each trial.

Eye position was monitored with an ASL EyeTrac 210 infrared limbus reflection system. Its analog output was sampled every 5 ms by an 8-bit serial analog-to-digital converter connected to the parallel port of the computer. Trials on which eye movements deviated more than 1° from fixation between target onset and response were discarded from analysis.

The left posterior neck muscles were continuously vibrated throughout the experimental blocks, to create proprioceptive input consistent with the body being twisted to the left. The neck muscles were vibrated with a flat 2.3 cm disk at a frequency of 100 Hz and an amplitude of 0.4 mm. In order to find the correct anatomical location for vibration stimulation, a small laser point was presented directly in front of the subject in the completely darkened room. Upon stimulation of the appropriate muscles at the correct point, each subject reported that the laser wandered to the right, providing an initial indication that the effective location for proprioceptive stimulation had been found [7,29]. In the control blocks, the vibrator was strapped to the left arm. This control stimulation (as used in previous patient studies [25,33]) should mimic any auditory or non-specific lateralised cueing effects of the neck vibration, but without changing the proprioceptive ‘head-on-neck’ signals that have been demonstrated to ameliorate neglect.

### 2.1.3. Procedure

The illumination of the central fixation light marked the beginning of each trial. After a delay of 400 ms the first lateral target was presented on one side. After the selected stimulus onset asynchrony (SOA, which varied between 0 and 105 ms, as described below), the second target was presented on the other side. Both target lights plus the fixation light remained on until the subject made an unsped judgement about which lateral target appeared first, at which point all three lights were extinguished, and there was an inter-trial interval of 1000 ms.

Each block contained 120 trials: eight trials at each of seven right-first SOAs (15, 30, 45, 60, 75, 90 and 105 ms), eight trials at each of the seven corresponding left-first SOAs, and eight trials where both stimuli were presented simultaneously (i.e. at zero SOA). These different SOAs were presented in a randomized order during each block. At the beginning of the experiment, the task was explained to the subjects and they were requested to make careful unsped decisions regarding which stimulus had appeared first. The experiment began with a practice block without any proprioceptive stimulation, which was not analyzed. Each subject then completed three blocks with neck-vibration and three blocks with the control arm-vibration. Half the subjects completed three blocks with neck-vibration first, while the remaining subjects ran three blocks with arm-vibration first.

The subjective straight ahead was measured at various points throughout the experiment in order to ensure that the proprioceptive illusion was maintained during extended periods of neck-muscle stimulation. At the start of the experiment, before any proprioceptive stimulation began, a baseline measure (10 samples) of

subjective straight ahead was taken. An additional 10 samples were recorded under neck vibration before the visual temporal-order task began, as well as 10 samples between each of the temporal-order blocks (with the vibratory stimulation — neck or arm — that had applied for the preceding temporal-order block), and also after the last block was completed. Finally, 10 more samples were taken 7 min after all stimulation had ended. The subjective straight ahead was measured by presenting the laser randomly at 10, 5 or 0° to the left or right of the objective straight ahead (as measured from the sagittal midline of the subject’s head and trunk) and asking the subject to center the beam using a hand-held controller (with left and right buttons) in the darkened chamber. This measurement was sampled-

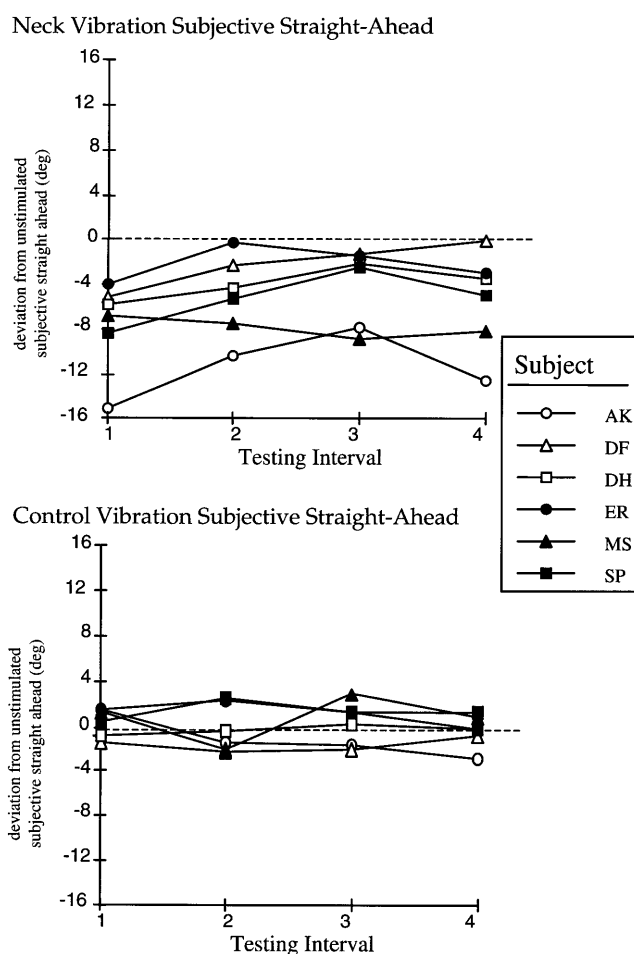


Fig. 1. Subjective straight ahead judgements during neck and control (arm) vibration in Section 2. Each data point is the mean value of ten measurements for one subject. Zero degree on y-axis corresponds to the mean of baseline measurements collected before and after vibration. A negative value indicates a subjective straight ahead judgement to the left of this baseline, while a positive value indicates that the laser was guided to the right of the baseline measurements. The x-axis distinguishes the different points in time at which the measurements were taken, between blocks of temporal-order testing, to allow assessment of whether the proprioceptive manipulation was effective throughout the study.

10 times at each of the points in the experiment that were listed above.

#### 2.1.4. Results

We first examined whether neck vibration was effective in biasing the subjective straight ahead throughout the experiment. A baseline subjective straight ahead measurement without proprioceptive stimulation was computed for each subject by taking the mean of measurements collected before stimulation was initiated, along with the data collected 7 min after all stimulation had ended. We then computed measurements taken during proprioceptive stimulation between blocks of the temporal-order task, scoring these relative to the unstimulated baseline, with all 10 samples at each interval averaged to compute a single value.

These data are plotted in Fig. 1, showing the performance of individual subjects during both neck and arm stimulation at each of the four testing intervals (i.e. before the first block of temporal-order testing; between the first and second block; between the second and third block; and after completing the third block of temporal-order trials for that stimulation condition). Under neck stimulation, subjects placed the laser point at a mean of  $5.5^\circ$  (standard error:  $1.5^\circ$ ) to the left of the unstimulated baseline. During arm stimulation, subjects placed the laser point  $0.3^\circ$  (standard error:  $0.5^\circ$ ) from their unstimulated baseline. A sign test was performed for each measurement (i.e. the means of the 10 samples collected before, between and after each block) and the two-tailed binomial probability derived. This confirmed that subjective straight ahead differed significantly from baseline during neck vibration. Indeed, all 24 measurements taken under vibration (6 subjects, each at 4 points in time; before the experiment, between blocked conditions and immediately after the experiment) were to the left of baseline,  $P < 0.001$ . Measurements during arm vibration did not differ significantly from the baseline measurement (10 measurements to the left and 14 to the right of baseline,  $P < 0.54$ ). A paired two-tailed  $t$ -test confirmed that performance was significantly different under neck vibration than under arm vibration ( $t(5) = 3.9$ ,  $P = 0.01$ ).

All subjects showed the same pattern. During neck-muscle stimulation, the subjective straight ahead deviated to the left, remained deviated throughout the period of vibration, and returned to near baseline after stimulation was terminated. In contrast, the arm vibration did not cause any consistent shifts of the subjective straight ahead. These data thus provide clear evidence that the neck muscles were stimulated appropriately throughout our experiment, producing a systematic bias in the egocentric coding of space (a deviation of the subjective straight ahead), just as documented in previous studies of normals and neglect patients [7,29,32,33].

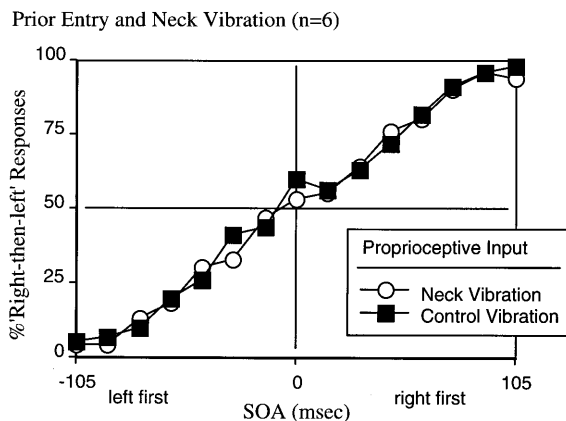


Fig. 2. Data from the visual temporal-order task of Section 2. The datapoints show frequency of 'right-then-left' responses at a given SOA. Negative SOA values indicate that the left target was presented first, positive values indicate that the right target preceded the left target, and SOA values of 0 indicate that both targets were presented simultaneously. Note the great similarity between curves obtained during neck vibration and those obtained during arm vibration.

We now turn to data from the visual temporal-order task. Trials where the eye blinked or deviated more than  $1^\circ$  to left or right of fixation were excluded. This amounted to 11 and 10% of all trials in the arm and neck stimulation conditions, respectively (most of these exclusions were due to blinks). The mean visual temporal-order results after these exclusions are given in Fig. 2. As can be seen, the results were virtually identical for the two different vibration conditions, suggesting that neck-muscle vibration did not bias covert attention towards one side in the visual temporal-order task, even though it clearly did produce a substantial shift in the subjective straight ahead.

The percent of right responses were computed for each subject at each SOA. An arcsin transformation of the data was applied to normalize the data. A repeated measures ANOVA was then conducted with two factors: SOA (15 levels, for each successive SOA separated by 15 ms) and vibration condition (neck versus arm vibration). This ANOVA revealed a main effect of SOA,  $F(14, 70) = 45.76$ ,  $P < 0.0001$ , indicating that right responses were modulated by SOA, increasing as the right events led by more time, as would be expected (see Fig. 2). However, there was no main effect of vibration condition ( $F(1, 5) = 0.04$ ,  $P < 0.68$ ), demonstrating that the overall proportion of right versus left responses was not affected by vibration type (neck versus arm). If neck vibration had specifically affected spatial attention and thus prior entry, this should have produced an interaction between SOA and vibration condition (i.e. evidence that neck vibration shifts the point of subjective simultaneity). However, the ANOVA revealed absolutely no tendency for any such SOA by vibration interaction,  $F(14, 70) = 0.8$ ,  $P < 0.67$ .

### 2.1.5. Discussion

Neck-muscle vibration did not produce any shift of covert visual attention towards one side as measured by the sensitive [49,52,57,58] temporal-order measure, even though it consistently shifted the subjective straight ahead in the expected leftward direction throughout the neck stimulation (see Fig. 1), by more than 5° on average. This appears to rule out any straightforward explanation for previous effects of neck-muscle vibration upon neglect that are based solely on covert attention being shifted along with the apparent postural change that neck vibration induces. Our results offer no support for the view that afferent proprioceptive input, consistent with changed head-on-trunk posture, normally biases covert visual attention in the corresponding direction. We return in the General Discussion to consider possible alternative accounts for the neck-vibration effects on neglect.

## 3. Experiment 2

Our next experiment examined whether a further sensory manipulation that is known to influence spatial neglect — namely, caloric vestibular stimulation — can affect the direction of normal covert visual attention. Numerous studies have now reported that a variety of neglect symptoms can be ameliorated temporarily if the patient receives an injection of cold water into the left auditory canal [5,10,14,21,26,32,51,50,53]. Injecting cold water in this way causes convection currents in the vestibular system, and shifts judgements of the subjective straight ahead towards the left in both normals and in neglect patients [29,32].

Several possible accounts for the effects of caloric vestibular stimulation on neglect have been forwarded (e.g. [12,32]). One possibility is that the stimulation biases the patient's gaze and thus visual input towards the contralesional side that is usually neglected. An observation apparently in line with this notion is that vestibular stimulation produces ocular nystagmus in both normals and neglect patients. Indeed, this effect on eye-movement patterns was the original basis for the use of caloric vestibular stimulation with neglect patients in clinical settings [55]. However, many of the subsequently documented effects on neglect cannot be attributed merely to deviations in gaze altering the visual input [9,14,50,51]; see discussion in Karnath et al. [26]. Nevertheless, the existing effects of caloric stimulation on neglect could, in principle, remain compatible with the notion that vestibular stimulation may bias covert attention towards one side, as well as overt movements.

Surprisingly, nobody has to our knowledge tested whether caloric vestibular stimulation can shift covert attention towards one side in normals. Previous work

has shown that such stimulation can bias normal subjects' perception of the subjective straight ahead (similarly to the effects of neck vibration [29]), and can influence several other spatial judgements as well [64,66], such as line bisection. However, no study as yet has directly measured whether there is any influence of caloric vestibular stimulation on normal covert visual attention.

There are two methodological obstacles to overcome when designing an experiment to test this. First, the effect of caloric stimulation on vestibular inputs is fairly short-lived [6,12]. Hence, each block of attention measurements must be completed in a relatively short period of time. Second, the stimulation is inevitably quite uncomfortable, due to the coldness of the water and the dizziness it induces, which effectively precludes extended re-applications. This means that the test for any bias in covert visual attention must be fully completed as rapidly as possible. For these reasons, the rather laborious psychophysical procedure of the temporal-order task from experiment 1 seemed unsuitable for implementation in conjunction with caloric vestibular stimulation. We decided instead to use a simple reaction time (RT) task for visual targets. This task is easy and rapid, so a substantial amount of data can be collected in a very short interval. Moreover, visual detection RT is the conventional task used in the Posner cueing paradigm [39]; many studies have established that it is highly sensitive to covert spatial attention both in normals, and also in patients with neglect or extinction [36,38,62].

The final difficulty in testing for any biases of covert visual attention during caloric vestibular stimulation is that such stimulation tends to cause uncontrolled eye movements. Without a fixation marker, ice-water vestibular stimulation induces slow-phase nystagmus toward the stimulated ear [5,6,55]. If the eyes consistently wandered to one side, any observed performance effects in a visual task might then simply reflect the direction of the fovea, rather than covert attention. To suppress this nystagmus, we again had to provide a central fixation light, and monitor eye-position on each trial, just as for experiment 1. Note that several caloric effects on neglect have already been documented that cannot be due to eye-movements changing the stimulus input (e.g. [9,14,50,51]).

The rationale for experiment 2 can thus be summarized as follows. The documented effects of caloric vestibular stimulation on neglect patients might in principle be due to a shift in covert attention, in the direction of the usual shift in the subjective straight ahead. If so, then such caloric stimulation should produce similar shifts of covert attention in normals, who like neglect patients show systematic deviations in the subjective straight ahead following caloric vestibular

stimulation [29,32]. Accordingly, we might expect faster visual RTs on the left relative to the right following injection of cold water into the left auditory canal in normals. As a control for any non-specific effects of this injection, due to the arousal caused by the coldness, subjects also underwent blocks with comparable visual testing, but now with an ice-pack attached externally to the left side of the neck. Finally, in baseline blocks of visual testing, no iced stimulation was applied.

In order to optimise the measure of visual attention by collecting as much data as possible, only the visual RT task was run during the various stimulation condition. There was insufficient time for the subjective straight ahead to be measured within the same study, as discussed earlier.

### 3.1. Method

#### 3.1.1. Subjects

Eight new subjects participated. Ages ranged from 18 to 25 with a median of 20 years. The experiment and induction required an hour to complete. All subjects were paid for participation.

#### 3.1.2. Apparatus and materials

Subjects sat at a desk in a completely dark room. A bicolour (red and green) fixation LED was mounted 70 cm in front of the subject. It was flanked by two green target LEDs, each mounted 10° to left or right of fixation. Whenever the room lights were on (during eye monitor set-up and task description, and between blocks), the LEDs were hidden so that subjects did not know their exact location relative to the body. A chin rest minimized head movements. Subjects responded by pressing a single button directly in front of them. The experiment was controlled by an IBM compatible portable computer, with outputs and the eye monitor linked to the parallel port and the response key connected to the serial port. The procedure for eye monitoring was identical to experiment 1.

Vestibular stimulation was accomplished by injecting 30 ml of ice water into the left external auditory canal over a 1 min period. Frenzel glasses were used to check that nystagmus was induced in all subjects, thus confirming the effectiveness of the stimulation. Karnath et al. [29] have previously shown that all healthy subjects who demonstrated nystagmus ( $n = 17$ ), following identical vestibular stimulation of their left auditory canal, also placed their subjective straight ahead to the left (mean = 4.6°, S.D. = 3.8°). Furthermore, Rubens [53] reported that all neglect patients who exhibited nystagmus following ice water injection into the left ear ( $n = 17$ ) also showed improved performance for left visual stimuli. Thus, although the time restrictions did not permit full measurement of the subjective straight

ahead in the present study, there are substantial grounds for assuming that the present vestibular manipulation was sufficiently effective to induce a bias in covert visual attention, if any such causal link exists.

Pilot testing suggested that the subjective effects of the present caloric stimulation were initially very strong, but dissipated after 5 min, as confirmed by the nystagmus measures. Visual attention testing was therefore initiated immediately after caloric nystagmus was observed. In the condition controlling for any non-specific alerting properties of caloric stimulation, subjects had an icepack applied to the left side of their neck, secured by a medical neck brace. In the baseline condition, no iced stimulation was applied.

#### 3.1.3. Procedure

Each trial began when the central fixation LED switched from red to green; this light then remained green for the duration of the trial. Any peripheral green target LED was illuminated 400 ms later, on the left or right. The task was to press the button as soon as this target light was detected. The target remained present until response, or for a maximum of 800 ms. The fixation LED then switched to red to provide a 600 ms inter-trial interval.

Each block contained 40 trials with left targets, 40 trials with right targets and 20 catch trials where no targets occurred (included to prevent anticipatory responding), all in a random order. Every subject participated in seven blocks. During the first practice block, the subjects experienced no caloric stimulation. During each of the next three blocks, the subjects experienced each of the three possible caloric manipulations (none, ice pack on left of neck, or caloric vestibular stimulation) in an order counterbalanced across subjects. In the final three blocks, these three stimulations were repeated in the same order for that subject. Each block took approximately 2½ min to complete. There was a break of approximately 5 min between blocks, with the room remaining dark during these intervals.

### 3.2. Results and discussion

Data from trials where eye-position exceeded 1° from central fixation (or there was a blink) were excluded from analysis (8.6% of trials), as were data from the first (practice) block. Trials where the response was made less than 50 ms or more than 600 ms after target onset were also excluded (1.4% of trials). Subjects made false responses in 3.7% of the catch trials where no target was presented. The mean results from target trials are shown in Table 1. Caloric vestibular stimulation appears to have no effect, and indeed there is no evidence for a left visual-field RT advantage in any condition.

A two-way repeated-measures ANOVA was conducted on RTs, with stimulation type (none, icepack or vestibular) and target location (left versus right) as the factors. No main effect was found for stimulation type ( $F(2, 14) = 0.8, P < 0.46$ ). A trend was noted for side,  $F(1, 7) = 4, P < 0.09$ , with somewhat faster responses for targets occurring on the right side (overall mean RTs of 300 vs. 308 ms for right and left, respectively). This right visual field advantage has been found in several previous studies [42,67]. The critical test for the hypothesis that caloric vestibular stimulation of the left ear with ice-water may produce a corresponding shift of covert attention to the left comes from the possible interaction between side and stimulation. No such interaction was apparent ( $F(2, 14) = 2.2, P < 0.14$ ), suggesting that the interventions did not alter the left versus right pattern of performance in the visual task. This was found even though previous work [29,32] shows that exactly the same caloric vestibular stimulation shifts the subjective straight ahead towards the left, in every single subject for whom nystagmus is induced (such induction was confirmed here). Note that, if anything, the direction of the small numerical trend in the vestibular condition was opposite to the predicted effect of a left visual field advantage.

An identical ANOVA on the miss rates for visual targets (see Table 1) found no main effect of stimulation type ( $F(2, 14) = 1.6, P < 0.24$ ), or of target side ( $F(1, 7) = 0.1, P < 0.8$ ), and no interaction ( $F(2, 14) = 0.0, P < 0.97$ ).

This experiment investigated whether caloric vestibular stimulation has an influence on normal covert visual attention, analogous to the dramatic effect that has been reported for neglect. Despite many previous studies demonstrating that the present vestibular stimulation can reduce left-sided impairments in right-parietal patients with neglect [10,14,21,26,32,50,51,53,55], and also induced leftward shifts of the subjective straight ahead in normals [29,32], the present study found absolutely no evidence for any modulation of covert visual attention by vestibular stimulation in healthy subjects,

Table 1  
Mean reaction time and omission error rates for the visual detection task of Section 3, for targets appearing on the left or right of central fixation<sup>a</sup>

| Condition  | Reaction time (ms) |       | Omission rate% |       |
|------------|--------------------|-------|----------------|-------|
|            | Left               | Right | Left           | Right |
| None       | 307                | 295   | 0.6            | 0.6   |
| Ice-pack   | 312                | 309   | 2.5            | 2.6   |
| Vestibular | 304                | 295   | 1.4            | 1.6   |

<sup>a</sup> Data are presented for three interventions: no stimulation, ice-pack on the neck and caloric vestibular stimulation of the left auditory canal with ice-water.

using a standard and sensitive measure for visual attention [39].

#### 4. General discussion

In two experiments we examined whether normal visual attention can be modulated by two of the most effective interventions for short-term amelioration of visual neglect in right-hemisphere patients: neck-proprioceptive stimulation, and caloric vestibular stimulation. Although a bias in attention is by no means the only explanation for neglect [11,31,66], it is increasingly viewed as one likely component of the disorder [16,34,38]. It thus remained possible, prior to our study, that proprioceptive and vestibular stimulation might exert their beneficial effects on neglect primarily by shifting covert attention in the direction of the changed subjective straight ahead (i.e. towards the neglected side). If this is indeed the mechanism, then one should expect to find corresponding shifts of attention with the same stimulation in normals. However, our two studies found absolutely no evidence for any such attentional effects in normals under proprioceptive or vestibular stimulation, even though both studies used visual tasks that are known to be highly sensitive not only to spatial neglect and extinction [49,36,38,52], but also to normal attention [39,57,58].

One might ask whether firm conclusions can ever be based on negative results. Frick [20] discussed this issue at length, noting that negative results are particularly informative when: (a) sensitive measures are employed; (b) a 'good effort' has been made to demonstrate a positive result; and (c) the negative result is surprising and informative, given the context of previous positive results. We think our study may satisfy all three criteria. First, we used established measures of covert visual attention, which have previously been shown to be sensitive to lateral biases both in normals [39,57] and in neglect and extinction patients [38,49,52]. Second, we went to considerable lengths to make the proprioceptive and vestibular interventions identical to those that have previously produced positive effects in neglect patients. Third, the present negative results for normal attention contrast strikingly with the many positive effects of neck-vibration and caloric stimulation reported for neglect patients. They also contrast with the positive effects on subjective straight ahead judgements in normals, as confirmed here within experiment 1.

Furthermore, our main finding (i.e. that neither neck-vibration nor caloric-vestibular stimulation affects the direction of covert visual attention in normals) also contrasts strikingly with the effects that these same interventions have on ocular search patterns in exploratory tasks, not only for neglect patients, but also in normal subjects [26]. That is, there appears to be a

clear dissociation between the positive effects of these stimulations on mechanisms of overt search in normals, versus their negative effects on covert attention as found here. Nevertheless, as mentioned earlier, it should be noted that some of the effects of proprioceptive and vestibular stimulation in neglect patients cannot be attributed to overt shifts in receptors altering the visual input (e.g. [9,14,30,50,51]).

The present results may be reconciled with the positive effects of proprioceptive and vestibular stimulation upon neglect, if the latter are due to changes induced in internal representations of egocentric space (as previously argued by [27,64]), rather than to any shifts of covert attention per se. Similarly, they could be reconciled with the documented effects that vestibular, proprioceptive and opto-kinetic stimulation can have on the perception of body orientation in normals [13,19,24], if one assumes that these tasks primarily reflect an influence on spatial representation rather than covert attention. Some previous patient research with opto-kinetic stimulation in neglect patients [63] specifically supports this, as such stimulation altered spatial perception not only for the neglected contralesional limb, but also for the ipsilesional limb.

The exact mechanisms through which vestibular and proprioceptive inputs affect neglect patients' coding of egocentric space remain unknown, but recent evidence from single-unit recordings in monkey parietal cortex suggests some possibilities. In particular, work by Andersen and colleagues has revealed that trunk rotation (or vestibular or proprioceptive inputs consistent with such rotation) modifies the visual response of cells in posterior parietal cortex [2,3]. In particular, cells in monkey LIP are influenced by neck-proprioception but not by vestibular inputs, whereas the reverse applies for cells in area 7a [56]. There are several ways (e.g. see [40,41]) in which unilateral lesions to populations of such cells could produce contralesional neglect that would be modulated by neck-proprioception and/or caloric vestibular stimulation. Below, we briefly describe two concrete possibilities, to illustrate that they make contrasting predictions for whether the interventions that ameliorate neglect should also influence covert attention in normals.

Single-cell findings and human neglect data both suggest the existence of neural populations whose visual responses are influenced not only by retinal location, but also by the position of visual stimuli relative to the trunk. Such sensitivity can be generated by combining retinal information with proprioceptive and/or vestibular information [4]. We discuss such cells below as if they code in explicitly trunk-centered spatial coordinates, but the same arguments follow if they code in a 'mixture' of retinotopic and trunk-centred coordinates, via gain-modulation [4,40,41].

One possible account for the influences of trunk orientation, neck-muscle and vestibular stimulation on neglect, in terms of such neural populations, could argue that the visual area in front of the trunk midline may be over-represented within the normal system. A relatively large proportion of visually-responsive trunk-centric cells may code the space directly in front of the person's trunk,<sup>2</sup> since the effective 'working space' for many actions in daily life (e.g. visually-guided hand movements) may be fairly near the trunk midline. Thus, just as retinotopic cells in early visual areas over-represent information presented near the center of gaze (at the fovea), trunk-centric visual cells might over-represent space near the trunk midline.

The observed influences of trunk orientation and neck-vibration on neglect might then be explained in terms of the putative over-representation of space near the trunk midline by such 'trunk-centric' cells, even if the lesion does not damage these neurons directly. It would be sufficient for the lesion to produce a rightward shift in where the trunk midline is perceived as pointing, consistent with past findings on subjective straight ahead judgements in neglect patients [32]. When the perception of trunk midline is deviated towards the ipsilesional side, trunk-centric neurons would over-represent (and thus be most sensitive to) objects presented ipsilesional to the trunk's actual position. Such objects would benefit from the putative cortical magnification of stimuli near the (mis)perceived trunk midline, while those towards the actual midline and further towards the contralesional side would suffer relative to the normal situation. This could lead to many of the spatial biases associated with neglect, and also to the ameliorative influences of trunk rotation, neck vibration and caloric stimulation (which would in effect 're-centre' the biased representation of the trunk midline, see [27]).

For present purposes, the important point of this hypothetical 'cortical-magnification-near-trunk-midline' account is that it (wrongly) predicts that those visual tasks affected by neglect (such as the temporal-order and visual RT tasks used here; [38,49,52]) should also be spatially modulated by deviations in the subjective straight ahead in normals. This should shift the receptive fields of 'trunk-centric' units in normals just as for the patients, and thus bias their performance accordingly in those visual tasks that are sensitive to neglect. Hence an effect of neck vibration and caloric stimulation is clearly predicted for our experiments, contrary to our results.

<sup>2</sup> In fact, some parietal neurons under-represent the fovea, relative to other visual areas (e.g. [37]). However, it should be noted that many brain areas are damaged in most neglect patients, not just specific parietal regions. Moreover, few studies of single cells to date have examined the population representation of 'trunk-centric' space, as opposed to retinotopic space, for many different brain areas.

A second way of explaining the same neglect data again involves 'trunk-centric' units. However, unlike the first model, it does not assume any 'cortical magnification' for the region of space near the (perceived) trunk midline. Instead, it merely assumes that cells which cover the left versus right of trunk-centric space tend to be unequally distributed between the two hemispheres, with a majority being sensitive to visual information from the contralateral side (in agreement with existing physiological data from monkeys, see [1,45,48]); but note that in humans, there may be some hemispheric asymmetries for this). A lesion that damaged units in one hemisphere might then primarily impair representations for the contralesional side of 'trunk-centric' space. This would lead to contralesional neglect that shows the modulations observed [10,14,21,25,28,32,50,51,55]. Turning the trunk towards the contralesional side, or producing corresponding changes in postural input via neck vibration and/or caloric stimulation, should shift contralesional stimuli towards the relatively preserved ipsilesional side of the trunk-centric representation. Note that unlike the first suggested model, this particular explanation carries absolutely no implication that the same manipulations should spatially bias performance in normals. On this account, the neglect deficit is caused solely by the selective loss of some 'trunk-centric' units representing contralesional space; there would be no such loss of cells in the normals.

The two neurophysiologically-inspired models sketched above can both provide simple accounts for existing neglect data (on the effects of trunk orientation, neck vibration and caloric stimulation) in relation to the known properties of parietal neurons. However, the two models differ in whether the manipulations that influence neglect patients should also influence normals, in an analogous spatial manner. Only the second model correctly predicts that those interventions that strongly modulate neglect (i.e. neck-proprioceptive and caloric vestibular stimulation) should have no impact on normal covert visual attention, as we found. We therefore suggest that results from normals can shed light on possible accounts for neglect.

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