Overlapping neural circuits for visual attention and eye movements in the human cerebellum.

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Abstract:

Previous research in patients with cerebellar damage suggests that the cerebellum plays a role in covert visual attention. One limitation of some of these studies is that they examined patients with heterogeneous cerebellar damage. As a result, the patterns of reported deficits have been inconsistent. In the current study, we used functional neuroimaging (fMRI) in healthy adults (N=14) to examine whether or not the cerebellum plays a role in covert visual attention. Participants performed two covert attention tasks in which they were cued exogenously (with peripheral flashes) or endogenously (using directional arrows) to attend to marked locations in the visual periphery without moving their eyes. We compared BOLD activation in these covert attention conditions to a number of control conditions including: the same attention tasks with eye movements, a target detection task with no cueing, and a self-paced button-press task. Subtracting these control conditions from the covert attention conditions allowed us to effectively remove the contribution of the cerebellum to motor output. In addition to the usual fronto-parietal networks commonly engaged by these attention tasks, lobule VI of the vermis in the cerebellum was also activated when participants performed the covert attention tasks with or without eye movements. Interestingly, this effect was larger for exogenous compared to endogenous cueing. These results, in concert with recent patient studies, provide independent yet converging evidence that the same cerebellar structures that are involved in eye movements are also involved in visuospatial attention.

Keywords: visual attention, covert attention, eye movements, cerebellum, fMRI

1. **Introduction**

Traditionally, the cerebellum has been understood to serve two basic yet critical functions: the coordination of motor output (i.e., walking, eye movements, balance, reaching) and motor learning (for a historical review see Glickstein, Strata, & Voogd, 2009). In recent years, however, several studies investigating patients with cerebellar damage have suggested that the cerebellum may also play a crucial role in higher cognitive functions such as attention, memory, language, and emotion (Schmahmann & Sherman, 1998).

Although the role of the cerebellum in memory, language, and emotion have recently been increasingly reported in the literature (for recent reviews see Marvel & Desmond, 2010; Sacchetti, Scelfo, & Strata, 2009; Stoodley & Schmahmann, 2009; Stoodley & Stein, 2011), the role of the cerebellum in attention has remained more controversial. Specifically, whereas early patient and imaging studies by Courschene and colleagues (Akshoomoff & Courchesne, 1992; Allen, Buxton, Wong, & Courchesne, 1997; Townsend et al., 1999) seemed to indicate a clear role for the cerebellum in attention, other studies failed to find any attentional impairments in patients with cerebellar damage (Dimitrov et al., 1996; Golla, Thier, & Haarmeier, 2005; Haarmeier & Thier, 2007; Yamaguchi, Tsuchiya, & Kobayashi, 1998).

One influential theory, known as the "premotor theory" of attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Sheliga, Craighero, Riggio, & Rizzolatti, 1997), suggests that our ability to attend to the periphery (covertly, without moving our eyes) is the result of neural processes related to eye-movement preparation and control, which are carried out by a known network of brain regions including the posterior parietal cortex, frontal eye fields, and superior colliculus. According to this theory, the same neural mechanism that prepares one to move one's eyes also acts as a trigger for shifting attention from one location to the end-point of an intended eye

movement (Colby & Goldberg, 1999; Deubel & Schneider, 1996; Duhamel, Colby, & Goldberg, 1992). Given that eye movements and spatial attention appear to share common neural substrates in the cerebral cortex (Astafiev et al., 2003; Corbetta et al., 1998), one might also expect that regions of the cerebellum that are important for eye-movement control play a role in controlling shifts in spatial attention.

The fact that attention and eye movements are strongly related means it is important to control for eye movements when examining the role of a brain structure in attention. Posner and colleagues (Posner, Snyder, & Davidson, 1980; Posner, Walker, Friedrich, & Rafal, 1984) developed a paradigm specifically for this purpose. The paradigm measures covert attention: which are changes in location of spatial attention while the eyes remain fixated. During the covert attention task, participants fixate their eyes at one location and attend to peripheral locations presented on the screen to the left and right of fixation. At the beginning of each trial, a cue appears such as a flash of light in the periphery, or an arrow at fixation pointing to the side of space to which the participant is to attend. Following the cue, a target stimulus (e.g., a small circle) appears either in the same location that was cued (termed a "valid trial") or in the opposite uncued location (termed an "invalid trial"). Participants are reliably faster to respond when the target appears at the cued compared to the uncued location (i.e., the cueing effect) because their attention was previously cued to the location in which the target appeared. In contrast, on invalidly cued trials, the participant must reorient their attention from the cued location to the opposite uncued location to detect the target (Posner et al., 1980; Posner et al., 1984).

Previous studies that have examined covert attention in patients with cerebellar injury have produced mixed results. Specifically, Townsend and colleagues (Townsend et al., 1999) observed that patients with cerebellar damage or degeneration were slower to orient their attention within

the first 100ms following a cue compared to controls. Attentional orienting in these patients, however, was approximately normal about 800 ms after the presentation of the cue. These results suggest that cerebellar damage may have a greater effect on exogenous (i.e., reflexive) compared to endogenous (i.e., voluntary) attention. Interestingly, structural MRI measures linked the slowed orienting of attention in these patients to decreased volume in cerebellar lobules VI and VII, regions that are known to be part of the "oculomotor vermis" (for a review see Voogd, Schraa-Tam, van der Geest, & De Zeeuw, 2012). Other studies, however, have failed to observe the same orienting deficits in patients with cerebellar damage suggesting that the impairments in visuospatial attention were related either to impaired motor output, or to impaired saccadic eye movements, and not to attention per se (Dimitrov et al., 1996; Golla et al., 2005; Yamaguchi et al., 1998).

The inconsistent results reported in the literature may be due to a number of factors such as: 1) differences in the covert attention tasks used, 2) the notion that motor output problems (i.e., motor preparation, response selection) might masquerade as attentional deficits (Haarmeier & Thier, 2007; Ravizza & Ivry, 2001; Yamaguchi et al., 1998), and 3) the fact that many studies of attention in patients with cerebellar injury have used heterogeneous patient groups with diffuse damage (e.g., cerebellar degeneration, focal lesions, tumours) (Dimitrov et al., 1996; Golla et al., 2005). The use of heterogeneous patient groups may be a particularly critical problem because most of these studies examined the effects of cerebellar damage on visuospatial attention only at the group level. Thus, if there are one or two patients with selective lesions who *do* demonstrate clear attentional deficits, it would not appear in the overall group analysis. More to the point, if patients with lesions or degeneration in different structures within the cerebellum (e.g., vermis vs. lateral cerebellum) are placed in the same group, this implicitly assumes that all areas of the

cerebellum should be equally involved in attention (i.e., that any cerebellar lesion should lead to a deficit). This assumption would be clearly false for the cerebral cortex, and there is plenty of evidence to suggest that specific regions of the cerebellum also subserve specific functions (for a review see Glickstein, Sultan, & Voogd, 2009). In summary, the heterogeneity of results in the literature may simply reflect the heterogeneity of the patient populations studied. One notable exception to this is a recent study by Baier and colleagues (Baier, Dieterich, Stoeter, Birklein, & Muller, 2010). In their study Baier et al., were able to demonstrate that a specific sub-population of patients (8 out of a total of 26) with damage to oculomotor vermal structures were clearly slower at reorienting attention on invalidly cued trials compared to healthy controls, thus confirming the original findings of Townsend et al. (Townsend et al., 1999) that suggested a link between oculomotor structures in the cerebellum and the control of covert shifts of attention.

In the current study, we sought to provide independent but converging evidence for these findings in healthy individuals using functional neuroimaging. Specifically, in addition to the standard fronto-parietal networks that are commonly engaged in covert attention tasks (for a review see Corbetta & Shulman, 2002), we also wanted to see whether or not any covert attention-related activation could be observed in the cerebellum. For the purposes of the current experiment, there were three primary questions of interest: 1) Does the cerebellum play a role in visuospatial attention in the intact brain? 2) If so, is there any overlap in the regions of the cerebellum that are involved in generating eye movements and shifts of covert visual attention when manual motor outputs (i.e., button presses) are controlled for? And finally, 3) is there any differential involvement in the cerebellum in exogenous compared to endogenous covert attention?

Several previous brain imaging studies have observed cerebellar activation during covert attention tasks (Corbetta et al., 1998; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000;

Lepsien & Pollmann, 2002; Nobre, Gitelman, Dias, & Mesulam, 2000; Rosen et al., 1999). These studies, however, did not adequately control for motor outputs (i.e., button presses or eye movements), so the cerebellar activation in these studies is somewhat difficult to interpret. That is, it is unclear whether the cerebellar activation observed in these previous studies is due to cerebellar involvement in attention, or to the programming or execution of motor responses associated with task performance.

To address these concerns, we performed a block design fMRI study where participants completed separate sets of runs consisting of either an exogenous orienting task in which peripheral cues were used to attract attention, or an endogenous orienting task in which central arrow cues were used to direct attention. For both orienting tasks participants were required to detect the presence of targets via a button press. In addition, participants also completed a number of control tasks during the exogenous and endogenous runs. Specifically, participants completed: 1) an overt attention task, which was identical to the covert attention tasks but required participants to make eye movements, 2) a target detection task that was identical to the covert attention tasks but contained no pre-cues, and 3) a button press task in which participants had to press a button once approximately every two seconds without any spatial pre-cue or target detection required. Using this design we could directly compare regions in the cortex and cerebellum that were involved in attention and eye movements while controlling for button press responses and eye movements.

2. Material and Methods:

2.1 Participants

A group of fourteen neurologically healthy right-handed participants (8 male, mean age: 26.6

years, age range: 18-34 years) took part in two experiments. The order of the experiments was randomized such that half of the participants completed the peripheral cue (i.e., exogenous attention) runs first and half completed the central arrow cue (i.e., endogenous attention) runs first. All participants gave written consent and all experimental procedures were approved by the University of Western Ontario Health Sciences Research Ethics Board. Participants received remuneration for their participation.

2.2 Experimental setup

Each participant completed separate runs of exogenous and endogenous cueing within the same scanning session. During the exogenous and endogenous runs, the participant performed a covert attention task as well as a number of additional control conditions (see below). Thus each set of runs (exogenous vs. endogenous) were functionally independent from one-another (Figure 1). That is, the functional activation acquired during exogenous and endogenous covert attention tasks was compared with functional activation from control tasks collected within the same set of runs. For both sets of runs participants were lying on the scanner bed while they viewed a 20 cm (width) x 15 cm (height) screen at a distance of 29 cm via a mirror. All images on the screen were white on a uniform black background. Images were displayed on a rear-projection screen behind the MRI scanner at a resolution of 1024 x 768 and a refresh rate of 60Hz. In the center of the screen was a white 8mm x 8mm fixation cross. In addition, white boxes (1.3 cm x 1.3 cm), each subtending approximately 2.5° of visual angle were placed 4.25 cm to the left and right of fixation (approximately 8° from fixation), and served as cue and target locations for the covert attention tasks. Targets consisted of an asterisk 0.75 cm x 0.75 cm subtending 1.5° of visual angle.

Participants indicated the presence of the targets, or simply made button presses in the button press task, by pressing buttons on an MRI compatible button pad.

Although we did not have access to an MRI compatible eye tracker, we directly monitored fixation and observed eye movements in 8 of the 14 subjects using an MRI compatible infrared video camera that was zoomed in on one of the participant's eyes. These videos were recorded and later analyzed offline by two independent raters (see Results section for details). For both the exogenous and endogenous runs, participants had little trouble fixating during the tasks that required fixation, or making eye movements during the eye movement tasks. All 14 participants were experienced fMRI subjects who we know could fixate for long periods of time. Furthermore, each participant underwent a behavioural training session prior to the fMRI study in which they completed practice runs of each of the tasks. During this behavioural training session, none of the participants had any trouble fixating when they were asked to fixate or making eye movements when they were required to do so.

The exogenous and endogenous runs consisted of four functional runs, each run lasting ~9.5 min (i.e. 40 min for each set of exogenous or endogenous runs). A single run consisted of seventeen 20-s experimental blocks each preceded by a 14-s rest period (Figure 1). During each 14-s rest period a word cue was presented (just above fixation) that cued the participant to the experimental task that was to be completed in the next block (e.g., "attention" for the covert attention condition, or "eyes" for the overt attention condition). The four experimental tasks were presented in a pseudo-random order such that across all runs each task was preceded and followed by each other equally often without allowing a single task to occur more than twice in a row. The exogenous and endogenous runs were completed in a single scanning session and were separated by an anatomical scan (see imaging procedures) at the midpoint of the scanning session to allow

the participant to rest. Half of the participants completed the exogenous runs first, and half of the

participants completed the endogenous runs first.

--insert Figure 1 here--

2.3 Experimental tasks

2.3.1 Exogenous attention task

During the exogenous attention task, participants were told to *always fixate on the central cross*

while attending to the marked locations on the left and right. At the beginning of a trial, there was

a fixation period of either 300 or 600 ms. Then, one of the two peripheral boxes brightened by

increasing the thickness of the outline from 1mm to 4mm, thereby drawing the participant's

attention to that location. The target stimulus (i.e., an asterisk) appeared either at the cued location

(i.e., a valid trial) or at the uncued location (i.e., an invalid trial), either 300ms or 600ms following

the onset of the cue. Participants had 1 s to detect the target via a button press before the next trial

began. Each trial lasted exactly 2 s in order to coincide with the TR (see scanning parameters

below). Thus each 20 sec block consisted of 10 trials with half of the targets appearing on the left

side and half of the targets appearing on the right side. In addition, for the attention and eye

movement tasks, the cues were predictive of the target's location such that the target appeared at

the cued location on 80% of trials. Finally, the order of trials was randomized within each block.

Purely exogenous orienting tasks typically utilize non-predictive (i.e., 50% valid) peripheral cues

whereas in the current study we utilized predictive (i.e., 80% valid) peripheral cues. In this version

of the task, there is an initial exogenous shift of attention to the peripheral cued location, followed

by a later endogenous shift of attention (Bartolomeo, Sieroff, Decaix, & Chokron, 2001; Friedrich,

Egly, Rafal, & Beck, 1998). We employed predictive cues in both our exogenous and endogenous

orienting tasks in order to equate the probability information provided to participants. This was important to control, since the cerebellum is known to play a role in predicting both sensory and motor events (Ivry, 1996; Roth, Synofzik, & Lindner, 2013). If the predictability of the target location differed between the two attention tasks then it would be difficult to interpret whether any changes in BOLD activity were related to the visual nature of the cue (peripheral vs. central arrow), or to differences in predicting the location of the target.

2.3.2 Endogenous attention task

The endogenous attention task was identical to the exogenous attention task apart from one critical difference. Rather than the use of the brightening of one of the peripheral boxes to cue attention, we presented a solid white arrow (1.3cm x 0.7cm) just above central fixation. The arrow cue could point to the left or the right to indicate to the participant that they should direct their attention to the peripheral box on that side without moving their eyes. Again, participants *were told to always fixate on the central cross* throughout the task.

2.3.3 Overt (eye movement) attention task

The overt (i.e., eye movement) attention tasks in both the exogenous and endogenous cueing runs were identical to the respective attention tasks except for one critical difference. Specifically, participants were told to make both a simultaneous button press as well as an eye movement to the target location when the target appeared. Participants were told to bring their eyes back to fixation as soon as the target disappeared prior to the beginning of the next trial. It is important to note that although it is possible that a participant could make an eye movement prior to a button press, it would not pose a problem for our analysis. We simply wanted to ensure that

participants made eye movements in our overt attention condition in order to be certain that oculomotor structures in the cortex and the cerebellum were engaged so that we could compare these regions to those involved in covert attention. As such, the exact timing and accuracy of saccades was not important to us, only that saccades to the target location were generated when required.

2.3.4 Detection task

The detection task in both experiments was exactly the same as the two attention tasks with the only difference being that the participant had to detect targets that appeared on the left or right equally often without any preceding spatial cue. Participants always maintained fixation during the detection task. This task was used to compare with the covert attention tasks in order to isolate the BOLD activation related to the processing of the cue. That is, both covert attention and detection require shifts of attention and button presses. However, only the covert attention tasks required the participants to direct their attention to the cued location prior to target onset. Thus, by subtracting BOLD activation associated with target detection from activity associated with covert attention we could isolate the response to the cue.

2.3.5 Button press task

During the button press task, participants viewed the fixation screen (i.e., with the cross and the two peripheral boxes) and were told to make a button press every 2 s. To help participants pace their responses properly, the screen display would briefly change from the fixation screen to a black screen and back to a fixation screen every 2 s to act like a metronome. This task essentially required participants to view the same fixation display as the other tasks and make the same

number of button presses at the same frequency in a 20-s period without any spatial cues or target

detection.

2.4 Procedures for fMRI

Scanning was performed on a 3T Siemens Tim Trio MRI system with a Siemens 32-channel head

coil (Erlangen, Germany). An anatomical scan was performed encompassing the whole brain. This

was achieved by collecting 192 one-mm thick slices using a 3-D T1-weighted acquisition sequence

(TI = 900 ms, TE = 3.43 ms, TR = 2300 ms, flip angle = 9°). The in-plane resolution of the

anatomical scans was 256 pixels × 240 pixels.

To collect the functional data, we used a T2*-weighted echo-planar imaging sequence

(TE = 25.0 ms, TR = 2000 ms, flip angle = 78°) for BOLD acquisition. The field of view was

16.8 cm × 16.8 cm with an in-plane matrix size of 80 pixels × 80 pixels. Each image covered the

whole brain and consisted of 38 slices oriented parallel to a line connecting the base of the

cerebellum to the base of the orbital frontal cortex (voxel size = 3.0 × 3.0 × 3.5 mm). There were

no gaps between slices.

2.5 Preprocessing of the fMRI data

SPM8 (Statistical Parametric Mapping software; University College of London, London, UK;

available at: http://www.fil.ion.ucl.ac.uk/spm) was used to preprocess the fMRI data. We motion

corrected the functional data by aligning all volumes to the third volume of the first run. The first

two volumes in each run were excluded because they might not be representative of steady state.

A slice-time correction algorithm was used to correct for differences in acquisition times between

slices by re-sampling all slices to match the first slice. Anatomical MRIs were then transformed into standardized space using the template brain from the Montreal Neurological Institute (MNI; McGill University, Montreal, Quebec, Canada). The functional data were then co-registered to the anatomical MRIs into standardized space and re-sampled to an isotropic voxel size of 2.0 mm. A Gaussian filter was used to achieve a final 7-mm full-width half-maximum of smoothing in the data.

To achieve a more accurate inter-subject alignment of the cerebellum, we also used the SUIT-toolbox for additional processing of the fMRI data (Diedrichsen, 2006; available at: http://www.icn.ucl.ac.uk/motorcontrol/imaging/suit). After the motion and slice time correction steps described above, we used the SUIT toolbox to isolate the cerebellum in each participant's anatomical MRI and transformed these images of the cerebellum into MNI space using a nonlinear deformation algorithm and the SUIT cerebellum as a template (Diedrichsen, 2006). The functional data were then co-registered and cropped to the anatomical normalized images of the cerebellum and re-sampled to an isotropic voxel size of 2.0 mm. A Gaussian filter was then used to achieve a final 7-mm full-width half-maximum of smoothing in the fMRI data of the cerebellum. Cerebellar functional data smoothing was done *after* co-registration to the cerebellum in order to eliminate the possibility that activation in cortical visual areas could erroneously appear as activation in the cerebellum. Drift was removed during statistical analyses by modelling a high pass filter (cut-off = 128 s) in the general linear model.

2.6 Statistical analyses of the fMRI data

Statistical analysis of the fMRI data was performed in two stages. For the first stage, we modelled, at the level of each individual, the time course of the response for each condition and convolved

this time course with a standard double-gamma hemodynamic response function. After performing the first level of analysis in all participants, we then used the first functional run from the exogenous and endogenous cueing sets of runs as functional localizer runs to define the fronto-parietal "attention network" that is commonly active in covert attention tasks (e.g., Corbetta & Shulman, 2002). We accomplished this using a random-effects model to test whether or not BOLD was greater in the attention (i.e., exogenous and endogenous) relative to the button press tasks. This contrast allowed us to isolate activation that was related to attention with the motor response component (i.e., a button press) removed. For each of these functional localizer runs we used a cluster analysis to correct for multiple comparisons in a whole-brain volume of 1000 cm^3. This yielded a threshold size of 352 mm^3 (i.e. a threshold size of 44 voxels with an isotropic voxel size of 2 mm) for reporting a cluster of voxels with a P-uncorrected value of less than 0.001 as being significant at Pcorr < 0.05.

From this contrast (described above), we identified brain areas that were significantly engaged in the "attention network" so that we could then carry out a regions-of-interest (ROI) approach for fMRI data acquired in the three remaining functional runs in each set of runs. An ROI approach on the data from the remaining functional runs was chosen over a voxel-wise based approach so that we could synthesize results obtained from a complicated 2×3 factorial design more easily. To perform the ROI analyses, we created spheres with a radius of 4 mm centered at the peak coordinates of all brain areas that we identified as being part of the "attentional network" and extracted from each of these spheres the participant's beta-weight values for each condition using the MarsBar toolbox for SPM (Brett et al., 2002: available at http://marsbar.sourceforge.net). For each ROI, an ANOVA was performed on the beta-weight values using Cue Type (exogenous and endogenous) and Task Type (covert attention, overt attention ((i.e., covert attention + eye

movements), and detection) as within-subject factors. Tukey's HSD tests, which corrected for multiple comparisons between conditions, were used to make pair-wise comparisons. Results surviving this correction are denoted by asterisks (*) in the Figures in the Results section. Results that we report for the cerebellum were derived from fMRI data preprocessed with the aid of SUIT while all other results reported in the rest of the brain were derived from fMRI data preprocessed without SUIT. Additional corrections for multiple ROIs using the Bonferroni method were also applied (i.e., $P_{new} = P_{old} \times 13$ ROIs; Dunn 1961). Results surviving this additional correction are denoted by daggers (†) in the Tables and the Figures in the Results section.

2.7 Recording and analyses of eye positioning

Eye movements were recorded in the scanner in 8 of 14 subjects using an MRI compatible infrared video camera (MRC Systems, Heidelberg, Germany) zoomed in on one of the participant's eyes. The use of an infrared camera made the pupil of the participant clearly visible in the video which made it easy to detect any eye movements that occurred. Given that the target locations were 8° from fixation, eye movements that would have brought the target into central vision were easily detected. In addition to video recording the eye movements of 8/14 participants in the fMRI scanner, all participants completed a pre-scanning behavioural session to familiarize themselves with the tasks. During this behavioural testing session, eye movements were watched closely by the experimenter and again none of the participants had any trouble maintaining fixation or making eye movements in accordance with our instructions.

To analyze the eye movement data, we had two independent observers who were blind to the hypothesis of the study code the eye movement videos from the 8 participants for whom we

were able to use the MRI compatible video camera. The infrared camera we used made the participant's pupil clearly visible which enabled us to easily detect any eye movements made away from fixation. For this analysis, the independent observers noted when any eye movements were made away from fixation, how many eye movements were made, and at what time the eye movements were made during each run. Given that each run was comprised of 20 sec task blocks with 14 sec rest periods, this allowed us to link the time the eye movements occurred in each video with the specific task that the participant was engaged in at the time. We then calculated the mean number of eye movements made in each task (covert attention, overt attention, detection, and button press) for the exogenous vs. endogenous runs. These data were then analyzed using t-tests.

The number of eye movements made in each condition was not entered as a covariate in the fMRI analysis. This is because part of the study's purpose (i.e. aim 2) was to compare fMRI-activation with and without eye movements. Entering eye movements as a covariate would have removed these effects of interest. As it turned out, the number of eye movements that were made in the exogenous and endogenous conditions did not differ (see Results) – making investigations comparing between exogenous and endogenous cueing conditions possible without eye movements being a nuisance variable.

2.8 Statistical analyses of the button-response data

In order to verify that the participants performed the attention tasks (both covert and overt) as expected we analyzed the behavioural data from the fMRI scanning sessions. Specifically, for each participant we computed the average reaction time (RT) for each condition for the both the covert and overt attention tasks for either the exogenous and endogenous conditions. We then removed any reaction times that were below 150ms and greater than 2SD above the participant's mean RT

for that condition. These data were then analyzed using within subject ANOVAs with cue (valid vs. invalid), SOA (300ms vs. 600ms), and task (covert vs. overt) as the within-subject factors.

3. Results

3.1 Behavioural data

Analysis of the behavioural data from the exogenous runs revealed significant main effects of cue (F(1,13=44.13, $p<.0001$), SOA (F(1,13==83.49, $p<.0001$), and task (F(1,13=12.51, $p<.004$). Specifically, participants were faster for valid (370ms) compared to invalid trials (433ms), faster for trials at the 600ms (383ms) compared to the 300ms SOA (420ms), and faster to respond to trials in the covert (356ms) compared to the overt (447ms) attention task. No interactions were significant.

Analysis of the data from the endogenous runs revealed an identical pattern of results. That is, we observed significant main effects of cue (F(1,13=127.11, $p<.0001$), SOA (F(1,13=41.10, $p<.0001$), and task (F(1,13=17.66, $p=.001$). Again, participants were faster for valid (345ms) compared to invalid trials (415ms), faster for trials at the 600ms (367ms) compared to the 300ms SOA (393ms), and were faster to respond to trials in the covert (341ms) compared to the overt (419ms) attention task. No interactions were significant.

3.1.1 Eye movement data

We were unable to analyze data from one participant because the image contrast in their video recordings was too poor for us to monitor the pupil. Therefore, the data from the remaining 7 participants for whom reliable data could be extracted are presented in Table 1. We first compared the data coded from each of the independent observers for each task using independent samples t-

tests. This analysis revealed that there were no significant differences in the number of eye movements detected for each task between the two observers (all t's <1.9, all *p*'s >.09). Given that there were no difference in the number of eye movements detected between the two observers we collapsed across the two observers for our subsequent analyses. Following this, we then examined if there was a significant difference in eye movements for the same tasks in the exogenous versus the endogenous runs. The analysis revealed that there were no significant differences in the number of eye movements made for the same tasks between the exogenous and endogenous cueing runs (all t's<1.9, all *p's*>.10). Furthermore, there were no significant differences in the total number of eye movements made between the exogenous (M=182) and endogenous (M=177) runs (t(6)=1.25, *p*=.26). Given that there were no significant differences in eye movements between the exogenous and endogenous runs, and the extremely small number of eye movements detected in the two covert attention tasks (mean= 2.25 between the two experiments; Table 1), it is unlikely that any differences in fMRI BOLD activity observed between the exogenous and endogenous runs is related to differences in the number of eye movements that were made.

--Insert Table 1 here--

3.2 Imaging data

Given the complexity of our factorial design and the nature of the specific aims of this study, a localiser analysis was first performed to define areas in the *"attention network"*, and once these regions were determined, ANOVA was then used to examine effects of Cue Type and Task Type as well, as interactions between these two factors (see section 2.6 in Methods for details). Reporting results for all possible pair-wise voxel-wise contrasts would not provide an intelligible

synthesis of our experiments nor would most of these contrasts be informative and answer our specific aims. We first report regions which we defined from our localizer analysis and then report the results that we obtained from carrying out ANOVA in each of our ROIs, examining the effects of Cue Type (exogenous vs. endogenous) and Task Type (covert attention, overt attention, detection, button press).

3.2.1 Brain regions in the "attention network" engaged by our localizer runs

Figure 2 illustrates the results obtained from our whole-brain voxel-wise exploratory search for brain regions that were significantly engaged by our localizer runs (i.e., attention > button press). Note that this contrast allowed us to identify brain regions in which there was significant BOLD activation even after motor responses associated with task performance (i.e., button presses) have been controlled for. This network of brain regions consisted of the superior parietal lobule / intraparietal sulcus (SPL / IPS) in the two hemispheres, the middle occipital gyrus (MOG), the inferior parietal lobule / intraparietal sulcus (IPL / IPS) in the two hemispheres, the left fusiform gyrus (Fus), the more posterior portion of Fus in the two hemispheres (pFus), the left lateral-occipital area (LO), the frontal eye fields (FEF) in the two hemispheres, the right middle-temporal gyrus / superior temporal sulcus (MTG / STS), and lobule VI in the left cerebellar hemisphere as identified with the help of a probabilistic atlas of the cerebellum (Diedrichsen, 2006). All coordinates and t-statistical values of significant brain activation from this analysis are reported in Table 2.

--Insert Figure 2 and Table 2 here--

3.2.2 ROI analyses performed for the main experiment

Main effects of Cue Type were found in the left pFus and the left cerebellar lobule VI in which

there was greater activation in these ROIs for exogenous relative to endogenous cueing (Table 3;

Figure 3). Main effects of Task Type were found in the SPL / IPS in the two hemispheres, the left

Fus, the left LO, the FEF in the two hemispheres, the pFus in the two hemispheres, the right IPL /

IPS, and left cerebellar lobule VI (Table 3). Pair-wise comparisons, which corrected for multiple

comparisons across the different conditions, revealed greater BOLD activation in the overt

attention task relative to both the covert attention and detection tasks in all these ROIs except for

the right IPL / IPS. In contrast, the main effect of Task in the right IPL / IPS was driven by greater

BOLD activation in both the covert attention and overt attention tasks relative to the detection task

(Figure 4). We also found a Cue × Task interaction in the left SPL / IPS. This interaction was

driven by greater BOLD activation in the covert attention task during exogenous cueing relative

to endogenous cueing and, in addition, by greater BOLD activation during the overt attention task

relative to the covert attention task during endogenous cueing.

--Insert Figures 3 and 4 and Table 3 here--

3.2.3 Connectivity analysis.

In order to further investigate the role of the cerebellum in attention we conducted a connectivity

analysis by correlating the beta weights from the cerebellar ROI (left lobule VI) with the other

ROIs identified in the attention network for each task. We then applied a Bonferroni correction for

the number of ROIs (i.e., .05/12=.004). Significant correlations following this correction are

reported in Table 4. This analysis revealed that increases in BOLD activity in left cerebellar lobule

VI during the exogenous attention task correlated significantly with increases in BOLD activity in

both the left SPL and the right FEF within the fronto-parietal attention network. Significant correlations in the exogenous attention task were also observed in ventral stream areas such as left LO and the left pFus. Furthermore, there was a significant correlation in left FEF during the endogenous attention task as well as significant correlations within the right pFus and right IPL in the detection task that was included in the endogenous runs.

One potential criticism of our imaging results is that the activation we observed in the left cerebellum may in fact be activation from visual areas in the ventral stream that were mislocalized to the cerebellum. Note that we used the SUIT toolbox for SPM to circumvent this problem by isolating the cerebellum and aligning the functional data to it prior to any spatial smoothing (see Methods). This makes the potential for mislocalization unlikely. Nevertheless, to further address this potential criticism, we conducted a follow-up connectivity analysis for the exogenous attention task by using partial correlations to examine the relationship between activity in the cerebellar ROI and the other ROIs while controlling for the relationship between each ROI and the left posterior fusiform (pFus; i.e., the closest visual ROI to the cerebellar ROI). Following this analysis we then applied a Bonferroni correction for the number of ROI pairs with the left cerebellar ROI (i.e., .05/11=.005). The results of this analysis revealed significant correlations between left cerebellar lobule VI and the left SPL ($r(14)=.74$, $p=.044$ corrected), and left IPL ($r(14)=.77$, $p=.022$ corrected) within the "attention network."

--Insert Table 4 here--

4. Discussion

Numerous studies over the past decade have implicated the cerebellum in higher cognitive

functions such as working memory, language, and emotion (Marvel & Desmond, 2010; Sacchetti et al., 2009; Schmahmann & Sherman, 1998; Stoodley & Schmahmann, 2009; Stoodley & Stein, 2011). One area of research that remains more controversial, however, concerns the purported role of the cerebellum in visuospatial attention

In the present study, we sought to find independent evidence for the role of the cerebellum in visuospatial attention by having a group of neurologically healthy individuals complete exogenous and endogenous covert attention tasks, as well as a number of control tasks (i.e., overt attention, target detection, and button press), while undergoing fMRI. We had three primary questions that motivated the current study: 1) is there evidence for cerebellar involvement in covert visual attention? 2) If so, is there any overlap in the regions of the cerebellum that are involved in covert attention and those involved in eye movements? And 3), is there any differential involvement of the cerebellum in exogenous compared to endogenous attention?

Analysis of the behavioural data from the experiment indicated that participants were significantly faster to detect validly compared to invalidly cued targets, faster to detect targets at the 600ms compared to the 300ms SOA, and faster to respond in the covert compared to the overt attention tasks. These results conform to those of many previous studies demonstrating that peripheral cues and central arrow cues are effective in directing attention, even in the absence of eye movements (e.g. Posner et al., 1980; Posner et al., 1984). Furthermore, these data indicate that the tasks we used produced the behavioural effects of interest which allows us to have better confidence that the fMRI activation we are observing in our covert and overt attention conditions accurately reflect the brain activity related to these processes.

In order to answer our questions regarding the role of the cerebellum in visuospatial attention, we started off by using the first runs from the exogenous and endogenous cueing runs as

localizer runs to identify the "attention network." In this analysis (Table 2 & Figure 2), we identified regions where activation for the attention tasks (exogenous or endogenous) was significantly greater than activation for the button press condition. This contrast is important because it allowed us to localize regions where attention resulted in significant activation even after the motor response components of the attention tasks (i.e., button presses) were controlled for. The results of this analysis demonstrated significant activation in a number of sites which have been previously been implicated in a fronto-parietal "attention network" (Astafiev et al., 2003; Corbetta et al., 1998; Corbetta et al., 2000; Corbetta, Kincade, & Shulman, 2002; Corbetta & Shulman, 2002; Lepsien & Pollmann, 2002; Nobre et al., 2000; Rosen et al., 1999). Most prominently, these areas included the SPL/IPS and FEF bilaterally, as well as the left and right IPL and right STS. The SPL/IPS and FEF are thought to constitute a "dorsal attention network" that is bilaterally represented and is important for orienting attention to specific locations in contralateral space (see Corbetta et al., 2000; Corbetta & Shulman, 2002). In contrast, the IPL and STG are thought to form the core of the "ventral attention network" that is important for target detection and for acting as a "circuit breaker" in order to reorient attention towards salient events in the environment (see Corbetta et al., 2000; Corbetta & Shulman, 2002). This system is thought to be heavily lateralized to the right hemisphere (Corbetta & Shulman, 2002; Shulman et al., 2010). We were not able to completely isolate these two attention networks in the current study because we used a block design. In order to successfully distinguish between the two attention networks previous studies (Astafiev et al., 2003; Corbetta et al., 2000; Corbetta & Shulman, 2002; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005) have employed widely spaced event-related designs in order to separate cue related from target related activity. However, more important for the purposes of the current investigation, the localizer analysis also revealed significant activation

in left cerebellar lobule VI (Figure 2 and Table 2). This suggests that the cerebellum may in fact play an important role in controlling aspects of visuospatial attention, even when manual motor response components (i.e., button presses) are controlled for.

Using ROIs identified in the localizer analysis (described above), we then analyzed the remaining data from each set of runs to determine which ROIs showed differences in BOLD activation between cueing (exogenous vs. endogenous) and task (covert attention, overt attention, target detection) conditions, as well as to determine which ROIs showed interactions between these two experimental variables. The results of this analysis revealed a main effect of cueing condition where there was significantly greater activation in the left posterior fusiform – perhaps reflecting differences in visual stimulation between the two conditions – as well as left cerebellar lobule VI for exogenous compared to endogenous attention (Figure 3 and Table 3). This suggests not only that the left cerebellum is involved in attention (greater activation for attention > button press in the localizer), but also that the same region may be more involved in *exogenous* compared to endogenous attention. It is important to note that this finding cannot be explained by differences in task difficulty. Specifically, if task difficulty were responsible for the effects we observed then one would predict the *opposite pattern* of results. That is, greater activation for *endogenous* (i.e., "voluntary" or controlled) compared to exogenous (i.e., reflexive) orienting. In fact, within the attention-network we localized, there were no ROIs that showed greater activation for endogenous relative to exogenous cueing.

The exogenous orienting task we used in the study is not completely pure and does combine a few elements of endogenous attention. That is, we utilized predictive (i.e., 80% valid) abrupt onset peripheral cues to trigger exogenous shifts of attention (see Methods for details). Some could argue that combining elements of endogenous attention we may have interacted with processes

underlying exogenous orienting leading to a different pattern of activation in the cerebellum. While it is possible that the combination of exogenous (i.e., peripheral cues) with endogenous (i.e., predictive cues) attention may have led to some non-additive effect, it seems rather unlikely for the following reasons. First, many studies have shown that exogenous and endogenous orienting share largely overlapping neural networks (similar to the current study) (e.g. Rosen et al., 1999). Thus, it would be difficult to explain why the only region of the brain (other than left pFus) that demonstrated a main effect of cueing condition was in the cerebellum. Second, given that the cues were equally predictive of the target's location in the two cueing conditions, one can deduce that the most likely reason for the differences in activation observed in cerebellar lobule VI are differences in visual stimulation associated with the two cue types (i.e., peripheral vs. central arrow cues). Specifically, the abrupt onset peripheral cues used in the exogenous attention condition would have led to a stronger engagement of cerebellar oculomotor structures than central arrow cues. Interestingly, a previous study by Baier and colleagues (2010) used a similar orienting task (i.e., predictive peripheral cues) to demonstrated covert attention deficits in cerebellar patients with damage to oculomotor structures near our cerebellar ROI.

Our analyses also suggest that the region of the cerebellum that may be important for covert attention (lobule VI in the left hemisphere; Figure 2; Table 2) is also important for generating eye movements. Specifically, the main effect of task (Figure 4) demonstrated that activation in the overt attention (i.e., "Eyes") condition was significantly larger than activation for either the attention or detection tasks in the same left cerebellar ROI (lobule VI; (as well as all other ROIs except the right IPL).

In order to further investigate the role of our cerebellar ROI (left cerebellar lobule VI) in attention we also conducted a connectivity analysis where we correlated the beta weights for each

task in the cerebellar ROI with each of the other ROIs. The results of this analysis revealed that activity in the cerebellar ROI during the exogenous attention task correlated significantly with activity in other ROIs in the fronto-parietal attention network such as the left SPL and right FEF, as well as ventral stream regions (i.e., left LO and left pFus). In addition, during the endogenous covert attention task, activity in the cerebellar ROI correlated with activity in the left FEF. Therefore, the cerebellum helps to control attention by acting in concert with other nodes in the fronto-parietal network. Note that for the exogenous and endogenous orienting tasks the cortical ROIs that correlated with the cerebellum (i.e., the SPL and FEF) are regions that are known to be part of the "dorsal attention network" which is thought to play an important role in allocating attention to specific locations or tasks (Corbetta et al., 2000; Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002; Kincade et al., 2005).

To summarize then, we have presented evidence that 1) the cerebellum is involved in covert visual attention even when motor responses (i.e., button presses) are controlled for, 2) the same regions of the cerebellum that is involved in covert attention (lobule VI of the left hemisphere) is also involved in eye movements, 3) the cerebellum may be more engaged during exogenous than endogenous attention, and 4) the cerebellum helps control attention by working in collaboration with other nodes of the well-characterized fronto-parietal attention network.

Before we discuss the implications of these results, it is important to address some potential criticisms of our findings. First, one potential problem is that our cerebellar ROI may simply reflect fMRI activation from the ventral visual stream in the left hemisphere that was mislocalized to the cerebellum. Note that it was not possible to do a visual field analysis by examining left and right visual field cues and targets separately as we employed a block design which does not allow us to disentangle these different trial types. However, we feel that our cerebellar ROI cannot be

attributed to mislocalized visual activation for two reasons. First, we used the SUIT toolbox (Diedrichsen, 2006) to preprocess the fMRI data obtained in the cerebellum. Using this toolbox, we first isolated the cerebellum from the rest of the brain using SUIT, and all functional data were then co-registered to the cerebellum *prior* to any spatial smoothing. Thus, we are confident that the results that we report for the cerebellar lobule VI are in fact driven by the cerebellum and not by the adjacent extra-striate visual cortex. Another added benefit of using SUIT is that it also allowed us to compare the location of our activation with a probabilistic atlas to ascertain what part of the cerebellum was driving this effect. According to the SUIT probabilistic atlas, the ROI that we had identified as corresponding to the cerebellar lobule VI falls within an 86% probability of being cerebellar lobule VI.

Additional evidence comes from our follow-up connectivity analysis where we utilized partial correlations to examine the relationship between our cerebellar ROI and the other ROIs while controlling for activity in the left posterior fusiform gyrus (Left pFus), the closest visual ROI to our cerebellar ROI. Even after controlling for visual activity in the left pFus, we still observed significant correlations between activity in left cerebellar lobule VI and the left SPL and left IPL, two nodes in the fronto-parietal attention network. This is an important finding because if visual activity from the nearby left pFus had been mislocalized to the cerebellum then activity in the pFus and the cerebellum should have been highly correlated. Thus, if activity in the cerebellum was really activity from the pFus that was mislocalized, then controlling for this relationship (i.e., using partial correlations) should have completely eliminated (or at the very least greatly reduced) any correlations between the cerebellar ROI and the other ROIs. This was clearly not the case. Therefore, we are confident that the BOLD activity we observed in the cerebellum is not related to mislocalized visual activation, but is related to the cerebellum's role in attention given its

functional connectivity to other ROIs in the fronto-parietal network.

We can also rule out that the attention-related activation that we observed in the cerebellum may be due simply to motor responses associated with the task and not to attention per se (Haarmeier & Thier, 2007). In the initial localizer analysis (Figure 2; Table 1) the contrast we reported was attention > button press. In the button press task (see Methods) participants made the same number of button presses, with the same frequency (once every 2 seconds), over the same period of time as in all of the other tasks. Therefore this contrast essentially controls for button press responses and subtracts this activation out of the overall analysis. Another important argument against this criticism is the fact that the activation we are reporting is in the *left* cerebellum. It is well known that the cerebellum is organized ipsilaterally (i.e., the left cerebellum controls the left side of the body Nolte, 2002). Given that participants all responded with their *right* hand, one would assume that if this activation was associated with executing button presses then the activation would be in the *right* cerebellar hemisphere.

It is also unlikely that the attention related activation in the cerebellum is related to participants inadvertently making eye movements. An MRI compatible video camera zoomed in on one of the participant's eyes was used to directly monitor fixation and eye movements in 7 of our 14 participants. Our observations during the scanning sessions and the offline analysis of the videos from two independent raters revealed that participants had no trouble fixating during tasks that required fixation (i.e., covert attention, detection, button press) and no difficulty making eye movements during the overt attention tasks. Furthermore, formal statistical analyses of this data indicated that there were no significant differences in the number of eye movements made in each task between the exogenous and endogenous cueing experiments, as well as no difference in the overall number of eye movements made between the two experiments. It should also be noted that

all 14 participants were experienced fMRI subjects who underwent a behavioural training session

in the lab prior to the fMRI experiment in order to ensure that they understood each of the tasks.

During these training sessions, participant's eye movements were watched closely by the

experimenter and again, none of the participants had any trouble fixating or making eye

movements during the appropriate tasks. Given that the targets were located 8° to the left and right

of center in each of the experimental tasks any eye movements would have been easily detected.

Thus, we are very confident that the activity we observed in the cerebellum was not due to

differences in eye movements made in the exogenous vs. endogenous cueing tasks.

Another possible criticism of our work is that the activation we observed may in fact reflect

differences in task difficulty. Specifically, in our covert attention task a participant was simply

asked to make a button press to detect the target whereas in our overt attention task the participant

was asked to make both an eye movement, as well as a button press. This is consistent with the

observation that RTs for the overt attention task were longer than RTs for the covert attention task.

However, the differences in RT between overt and covert attention conditions may simply reflect

the fact that participants initiated eye movements just prior to button presses, hence the increase

in RT for overt attention. Note that this would not pose a problem for our results as the exact timing

of saccade or button press onset was not important to us. Our main concern was that participants

were initiating both button presses and eye movements in a given trial in order to ensure that the

neural structures involved in both attention and eye movements were engaged. This then allowed

us to determine whether these functions were controlled by distinct or overlapping neural

mechanisms in the cerebellum and cortex.

It is also important to point out that BOLD activity was higher for the overt attention (i.e.,

"eyes") condition compared to the covert attention condition in a majority of our ROIs (although

activity for covert and overt attention were equal in the right IPL). This also seems to imply that our overt attention condition may have been more difficult than our covert attention condition. However, previous research has demonstrated that there are significant increases in BOLD activity in the same brain regions when participants complete overt compared to covert attention tasks, even when the overt attention task does not require a button press (Astafiev et al., 2003). It may therefore be the case that eye movements simply engage the same structures more strongly than covert attention as programming and executing a saccade to the target location may place increased computational demands on the same neurons. Additional evidence that our results are unlikely to be attributed to differences task difficulty comes from the fact that the brain regions that are typically associated with increases in task difficulty are not active in our tasks. Specifically, previous studies examining task difficulty, and the brain regions engaged with increased cognitive demands, have observed increases in activity in regions such as the lateral prefrontal cortex, the anterior cingulate cortex, and the pre-supplementary motor area (for a review see Duncan, 2010). None of these regions were active in our comparisons suggesting that the differences observed between tasks are unlikely to be explained by differences in task difficulty.

Perhaps the most interesting finding in the current study was that we observed significant activation in the cerebellum regardless of whether participants were attending with or without making eye movements. This is consistent with the "premotor theory" of attention which posits that attention and eye movements are governed by the same neural circuitry (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994). Thus, according to the premotor theory of attention, covert shifts of attention are saccades that are planned in the direction of the cue, but not executed. The mere planning of the saccade is sufficient to shift attention toward the cued location (Rizzolatti et al., 1987; Rizzolatti et al., 1994). This theory is generally consistent with data from psychophysics,

neurophysiology, and functional brain imaging (Colby & Goldberg, 1999; Corbetta et al., 1998; Deubel & Schneider, 1996; Duhamel et al., 1992; Goldberg, Bisley, Powell, & Gottlieb, 2006; Nobre et al., 2000).

The activation we observed in the cerebellum for attention and/or eye movements was in lobule VI which is part of the "oculomotor vermis" (Voogd et al., 2012). Numerous brain imaging and neurophysiological studies have demonstrated that these regions are involved in generating eye movements, as well as saccadic adaptation (Barash et al., 1999; Desmurget et al., 2000; Glickstein, Sultan, et al., 2009; Hayakawa, Nakajima, Takagi, Fukuhara, & Abe, 2002; Robinson & Fuchs, 2001; Ron & Robinson, 1973; Stephan et al., 2002; Voogd et al., 2012). Interestingly, the outputs from lobule VI are sent to the superior colliculus (via the fastigial nucleus), another structure involved in generating eye movements and covert shifts of attention (Akaike, 1992; Glickstein, Sultan, et al., 2009; Krauzlis, Lovejoy, & Zenon, 2013; Voogd et al., 2012; Walker, Fitzgibbon, & Goldberg, 1995). In addition, our functional connectivity analysis indicated that increases in activation in cerebellar lobule VI correlated with increases in activity in several other ROIs, most notably the left SPL and right FEF. Thus, we can infer from the current results that the cerebellum likely controls covert attention via connections with the superior colliculus and its downstream targets, as well as through connections with other nodes of the fronto-parietal attention network (i.e., SPL and FEF). However, the specific role that the cerebellum plays in controlling covert attention must await future investigation.

An alternative explanation for our results is that the cerebellum might not be involved in covert attention per se, but might instead be involved in the *inhibition* of eye movements to a target location. Perhaps the best paradigm to use when examining saccade inhibition is the antisaccade task where, during antisaccade trials, the participant must inhibit a saccade to the target location

and instead make a saccade to the opposite location. In a recent meta-analysis of imaging studies examining the antisaccade task, Jamadar et al.(2013) observed increased activity in the left and right PPC, lateral prefrontal cortex, and anterior cingulate cortex in antisaccade trials compared to prosaccade trials. Interestingly, they also observed a significant increase in activity in the left cerebellar tonsil for antisaccade trials compared to prosaccade trials. However, the cerebellar tonsil is much more lateral than our cerebellar ROI which is located in lobule VI within the oculomotor vermis (Robinson & Fuchs, 2001; Voogd et al., 2012). Importantly, these regions are also thought to subserve different functions. That is, medial structures in the oculomotor vermis are thought to be critical for the execution of eye movements; however, regions in the lateral cerebellum are thought to be linked to higher level cognitive functions such as working memory, emotion, and language (Stoodley & Schmahmann, 2009; Stoodley, Valera, & Schmahmann, 2010). In short, while regions of the cerebellum may be involved in saccade inhibition these structures are distinct from those we observed in the current study.

Our results are consistent with a previous study by Townsend and colleagues (1999) demonstrating a significant correlation between lobule VI volume and attentional orienting deficits in cerebellar patients. Specifically, Townsend and colleagues (1999) observed that as the size of lobule VI *decreased* following brain damage, orienting deficits *increased*. A similar region of activation (i.e., the left posterior quandrangular lobe) was identified by Allen and colleagues (1997) in a functional imaging study which examined regions of the cerebellum involved in visual non-spatial attention independent of motor responses. Finally, our results are also consistent with a recent study by Baier and colleagues (2010) in which they demonstrated that only patients with damage to the vermis, culmen, and the inferior semilunar lobule had abnormal reaction times in a covert attention task. These regions are in close proximity to the activation we observed in lobule

VI.

One final point that warrants further discussion is that the activation we observed in lobule VI of the cerebellum was greater for exogenous compared to endogenous orienting. It is well known that abrupt onset events in the periphery (such as the exogenous cues used in this and many other experiments) are quite effective at attracting attention (e.g., Jonides & Yantis, 1988) as well as eye movements (e.g., Mulckhuyse, van Zoest, & Theeuwes, 2008; Schreij, Owens, & Theeuwes, 2008). However, in order for a central arrow cue to elicit a shift in the location of attention, or an eye movement, more time is needed, as the direction of the arrow must first be interpreted before the a saccade plan can be generated (Jonides, 1981; Muller & Rabbitt, 1989). Thus, one might assume that reflexively triggered attentional shifts and eye movements may lead to an increased engagement of oculomotor structures. This result is also interesting because it parallels earlier findings by Townsend et al. (1999) who found deficits in exogenous (i.e., within 100ms post target onset) but not endogenous (>800ms post target onset) orienting following cerebellar damage.

In conclusion, our data, along with those from recent patient studies, provide independent but converging evidence that regions of the cerebellum that are involved in the control of saccadic eye movements are also involved in the allocation of covert visual attention.

Acknowledgments:

Tables

Table 1. Eye movement data from 7 participants from the fMRI scanning session collapsed across the two independent observers.

| | Task: | | | |
Experiment:	Covert attention	Overt attention	Detection	Button press
Exogenous cueing	1.9	166.65	2.14	1.51
Endogenous cueing	2.6	160.01	1.08	0.16

Table 2. Brain regions identified as part of the "attentional network" from the localizer runs.

Brain Area	X	Y	Z	$T_{(13)}$	Cluster Size (mm³)
Left SPL / IPS	-24	-66	48	9.78	7,808
Left MOG	-32	-88	22	8.51	
Left IPL / IPS	-40	-40	50	7.93	
Left Fus	-32	-56	-14	7.63	3,912
Left LO	-44	-76	-8	6.66	
Right pFus	22	-88	-16	7.56	632
Right FEF	44	-2	50	7.29	1,944
Left FEF	-24	-8	54	6.70	2,392
Left pFus	-28	-86	-8	6.95	352
Right SPL / IPS	22	-64	58	6.86	6,296
Right IPL / IPS	34	-56	54	6.52	
Right MTG / STS	46	-62	10	5.92	1,168
Left cerebellar lobule VI	-6	-74	-23	6.50	352

Coordinates are in MNI space.

Table 3. Results from the ROI analyses

A.	Main effect of Cue Type Brain Area	$F_{(1,14)}$
	Left pFus	8.51
	Left cerebellar lobule VI	4.79
B.	**Main effect of Task Type Brain Area**	$F_{(2,28)}$
	Left SPL / IPS	5.99
	Left Fus	† 7.48
	Left LO	6.80
	Right pFus	† 19.66
	Right FEF	† 25.57
	Left FEF	† 25.45
	Left pFus	† 12.94
	Right SPL / IPS	† 8.34
	Right IPL / IPS	4.91
	Left cerebellar lobule VI	†14.43
C.	**Cue Type × Task Type Brain Area**	$F_{(2,28)}$
	Left SPL / IPS	3.95

Daggers (†) denote surviving an additional correction for multiple ROIs.

Table 4: Results from the connectivity analysis.

Condition	ROI	r	*p*-value (corrected)
Attention - Exogenous	Left SPL	0.71	0.025
Attention - Exogenous	Left LO	0.78	0.005
Attention - Exogenous	Right PMd	0.81	0.001
Attention - Exogenous	Left pFus	0.73	0.016
Eye - Exogenous	Left LO	0.79	0.004
Attention - Endogenous	Left PMd	0.75	0.001
Detection - Endogenous	Right pFus	0.70	0.030
Detection - Endogenous	Right IPL	0.74	0.012

Only significant correlations are listed. P-values are Bonferroni corrected.
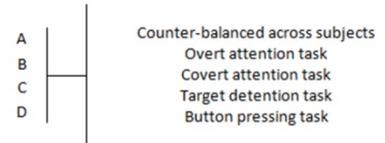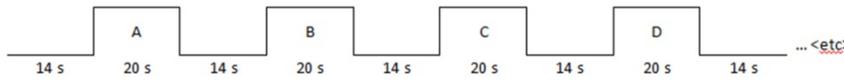
Figures

A Study Design

| A | A | A | A | Structural MRI | B | B | B | B |

A
B

Counter-balanced across subjects
Exogenous cueing condition
Endogenous cueing condition

B Run Design

| 14 s | A 20 s | 14 s | B 20 s | 14 s | C 20 s | 14 s | D 20 s | 14 s | ... <etc> |

A
B
C
D

Counter-balanced across subjects
Overt attention task
Covert attention task
Target detention task
Button pressing task
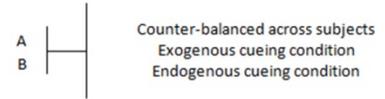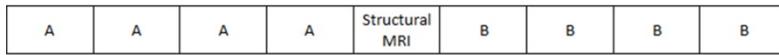
Figure 1. Overview of the study design. Participants completed 4 runs of either exogenous or endogenous cuing followed by a structural scan followed by 4 runs of the other cueing condition they did not do before the structural scan (A). Within a run, participants performed blocks of the overt attention, covert attention, target detection, and button pressing tasks (B). The order of the conditions (exogenous cueing, endogenous cueing) and tasks (over attention, covert attention, target detection, button pressing) was counterbalanced across the participants.
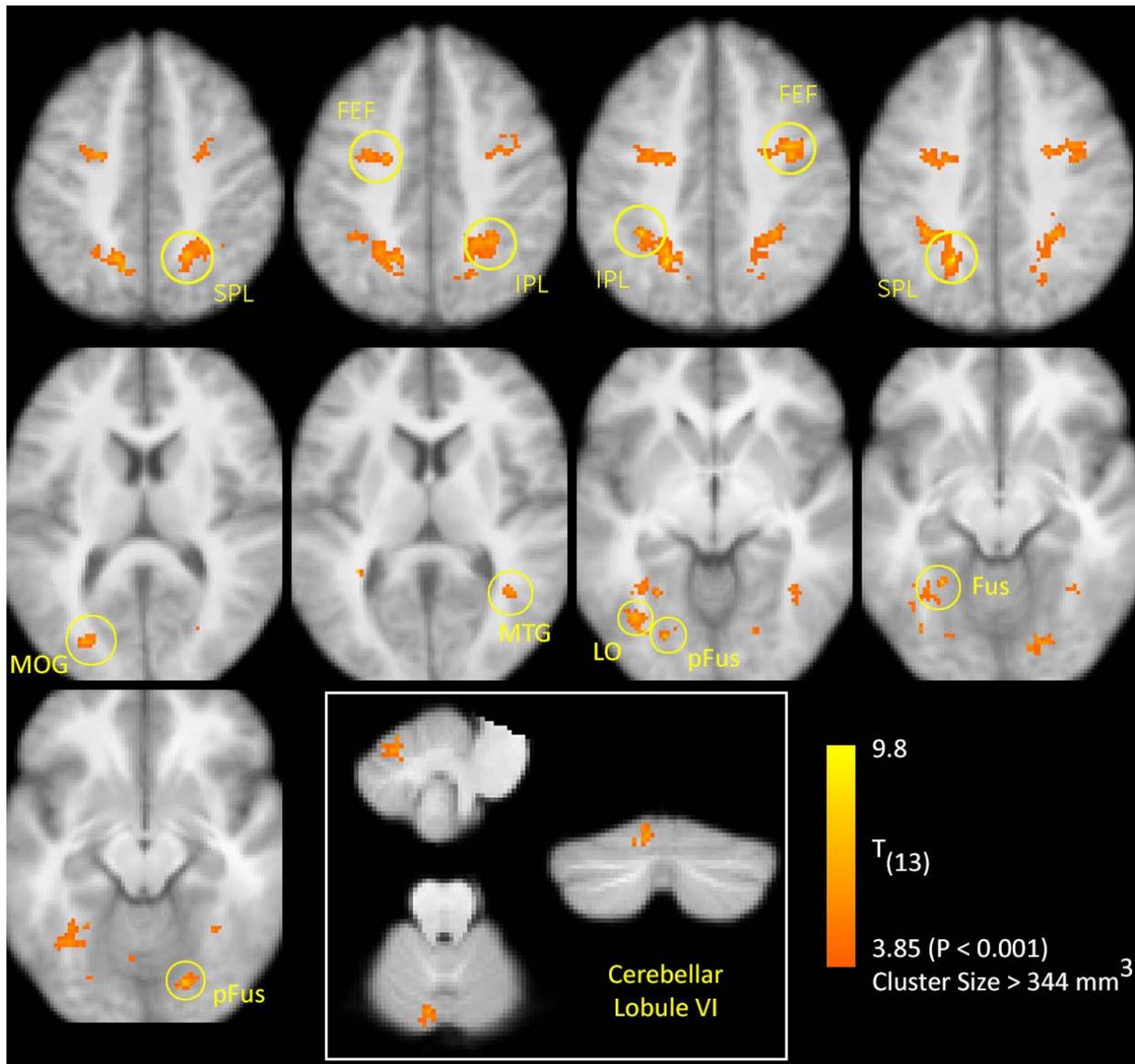
Figure 2. The "Attention Network". A group voxel-wise based analysis identified brain areas that were significantly more active for the "Attention" compared to the "Button press" conditions during the localizer runs in both the exogenous and endogenous cueing experiments. The F-statistical map was merged with the average anatomical MRI of all participants in standardized space and thresholded using the minimum given by Bonferroni correction and random-field theory for a whole brain analysis. See Table 1 for peak coordinates and F-statistical values for each of the brain areas shown in this figure.
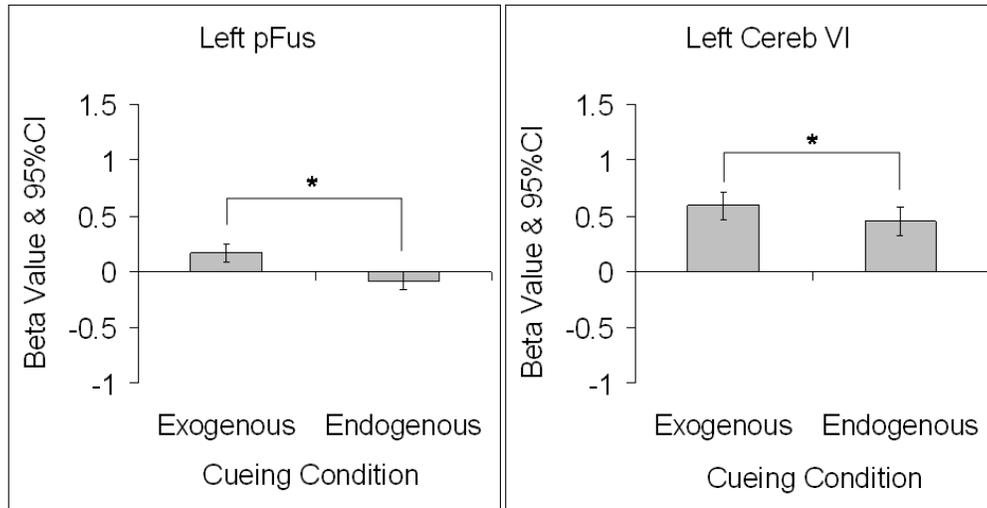
Figure 3. Main effect of cueing condition.
Graphs show the mean beta weights of BOLD data extracted from ROIs ± 95% confidence intervals for within-subject contrasts (Loftus and Masson, 1994). Asterisks (*) denote significant differences between conditions. See Table 2 for the statistical values of the ANOVA carried out on this data.
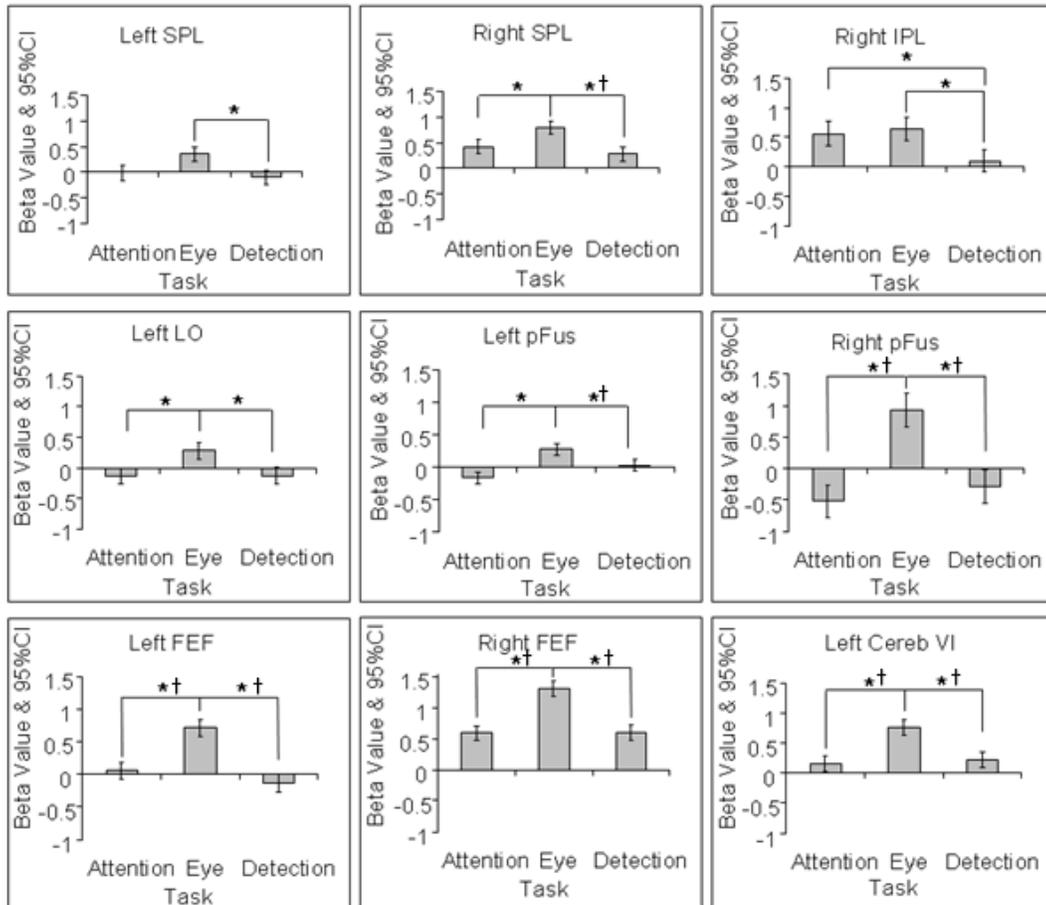
Figure 4. Main effect of task. Graphs show the mean beta weights of BOLD data extracted from ROIs ± 95% confidence intervals for within-subject contrasts (Loftus and Masson, 1994). Asterisks (*) denote significant differences after Tukey's HSD test were applied to correct for multiple comparisons between conditions. Daggers (†) denote results surviving an additional correction for multiple ROIs. See Table 2 for the statistical values of the ANOVA carried out on this data.

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