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Abstract: It is still an open question if the auditory system, similar to the visual system, processes auditory motion independently from other aspects of spatial hearing, such as static location. Here, we report psychophysical data from a patient (female, 42 and 44 years old at the time of two testing sessions), who suffered a bilateral occipital infarction over 12 years earlier, and who has extensive damage in the occipital lobe bilaterally, extending into inferior posterior temporal cortex bilaterally and into right parietal cortex. We measured the patient's spatial hearing ability to discriminate static location, detect motion and perceive motion direction in both central (straight ahead), and right and left peripheral auditory space (50 degrees to the left and right of straight ahead). Compared to control subjects, the patient was impaired in her perception of direction of auditory motion in peripheral auditory space, and the deficit was more pronounced on the right side. However, there was no impairment in her perception of the direction of auditory motion in central space. Furthermore, detection of motion and discrimination of static location were normal in both central and peripheral space. The patient also performed normally in a wide battery of non-spatial audiological tests. Our data are consistent with previous neuropsychological and neuroimaging results that link posterior temporal cortex and parietal cortex with the processing of auditory motion. Most importantly, however, our data break new ground by suggesting a division of auditory motion processing in terms of speed and direction and in terms of central and peripheral space.

Nov 6, 2015

Dear *Dr Murray*,

We are submitting a revised version of our manuscript "A selective impairment of perception of sound motion direction in peripheral space: A case study" for publication in *Neuropsychologia*.

We revised our manuscript in response to the reviewer's comments, and we feel that it has improved as a result of the revisions. We have also included a detailed response to all of the reviewer's comments. We hope that you will find the revised version of our manuscript suitable for publication in Neuropsychologia.

With best wishes on behalf of all authors,

Lore Thaler, Department of Psychology, Durham University, UK

Dear Prof. Murray,

Again we thank the reviewers for their careful consideration of our manuscript. We have addressed their concerns in the revised manuscript. Please see below our replies (in red) to the reviewers' comments (in black).

With best wishes, on behalf of all authors,

Lore Thaler

Reviewer #1:
1. I apologise to authors and editors for delay
2. I have read the revised manuscript and rebuttal and recommend publication.
3. I think there are interpretational aspects of the work that are explicit in manuscript about which readers can make up their own mind.
4. I do not agree with referee 2 about the need to match educational level in controls, over and above including subjects without cognitive deficits. I have no experience of this affecting spatial tasks but have never looked specifically and I would be interested to hear if there were any published literature. In any event the author rebuttal and analysis is reasonable.

We thank the reviewer for their positive evaluation of our manuscript.

Reviewer #3: Review of Thaler et al., "A selective impairment…"

The submitted manuscript presents a case study of one subject (MC) with extensive lesions of occipital, parietal, and temporal cortices. The focus of the study is on spatial hearing, in which MC exhibits interesting and specific deficits in the processing of auditory motion despite more normal performance on static spatial and other auditory tasks. Although the amount one can conclude from case studies is necessarily limited, the authors have done a good job in designing and executing experiments that tease out the various aspects of MC's deficit and presenting those data along side control-subject data.

We thank the reviewer for their positive evaluation of our manuscript.

The manuscript has undergone two previous rounds of reviews. My reading of the concerns raised in previous rounds convinces me that the authors have attempted to address each concern in the most rigorous fashion that is realistically possible given the nature of the study. The results add an interesting piece to the data on cortical mechanisms of spatial hearing. As the authors point out, one interpretation of the data in combination with previous studies of other patients appears to demonstrate doubly dissociated deficits.

I have no significant concerns with the design or execution of the study, or with the manuscript itself. I think the paper represents the data in a reasonable fashion that generally respects the limitations inherent in the case-study approach. My general comments focus mainly on interpretations of the data in light of spatial cue-processing in the auditory cortex.

1) A key finding is the dissociation in motion perception for central and peripheral auditory targets. The authors provide several discussion points regarding the possible origin of these effects, but one

issue I think might be worth considering is the following: Relative spatial processing (including motion processing) in peripheral space is likely to be more strongly dependent on the processing of spectral (versus binaural) cues than in central space. This is because the binaural cues do not change as rapidly with azimuth for eccentric targets as for central targets (in particular across the midline). One may thus consider azimuthal resolution in peripheral space to be somewhat akin to the resolution of front-back reversals (in which binaural cues are not useful), which are strongly enhanced by spectral cues.

Spectral-cue use is also more strongly dependent on stimulus familiarity and listening context than binaural-cue use. Thus, mechanisms affecting MC's deficit could potentially relate to representing the contextual and stimulus effects of spectral change beyond motion per se. For example, it is known from the work of Andy King's group at Oxford that cortical mechanisms are necessary for relearning the relationships between altered spectral cues and sound-source location. If MC's lesion impacts the descending corticocollicular pathways involved in such transformations, one might expect impairments and biases in any spatial computation that relies on them (i.e. peripheral but not central space). This is a particularly likely issue given that the stimuli incorporated HRTF measurements from a binaural manikin (unlikely to be acoustically close to MC's own HRTFs and therefore requiring a high degree of "relearning").

We thank the reviewer for this observation. We now realize that we had not addressed this issue at all, but we have now added a section in the discussion to address this (see also our response to the next comment).

2) A related issue is the overly strong conclusion (page 23 line 9-14) that peripheral motion and static location are processed independently in the posterior temporal and parietal cortices respectively. If spatial processing for moving peripheral targets depends on different acoustical cues (spectral) than static location or motion in central space (binaural), than different degrees of "auditory" processing per se (in the posterior temporal lobe) would be expected. I am not quite sure how this interacts with the ipsilaterality of MC's apparent motion bias; however, spectral changes with azimuthal motion are complex and likely to drive both increases and decreases in frequency-specific sound energy at the two ears. The cues themselves, and the functional anatomy of ascending and descending pathways may provide some clues. I suggest looking at the work from Andy King's lab and consulting with Ewan Macpherson at Western, a world expert on the use of spectral cues for dynamic sound localization by human listeners.

One thing to keep in mind is that all peripheral tasks we used (i.e. static location, motion speed, motion direction) would rely on the spectral cues more heavily than on the binaural cues.
Yet, only motion direction perception was impaired in MC.
The selective deficit in MC in the latter task would suggest then, that processing of spectral cues for some sorts of perceptual judgment (i.e. static location, motion speed) is fine, but that it is impaired for the other perceptual judgment (motion direction).
In sum, we think that the difference in the acoustic feature to be analysed (spectral, binaural) as well as the perceptual attribute that needs to be judged (location, motion speed, motion direction) have to be considered together to describe the deficit.
We thank the reviewer for drawing our attention to the issue of spectral vs. binaural cues and their relevance for the different tasks. Following the reviewer's comments we have added a section in the discussion to address these issues.

Page 22, bottom para
"One thing to also consider in this context is the likelihood that different acoustic cues would be used for different tasks. Specifically, spatial processing (including motion processing) in peripheral

space is likely to depend more on the processing of spectral (versus binaural) cues than spatial processing in central space, which is likely to rely more on binaural cues. This is because binaural cues (i.e. ITD, ILD) do not change as rapidly with azimuth for peripheral targets as they do for central targets, in particular across the midline (e.g. King, Schnupp & Doubell, 2001; MacPherson & Middlebrooks, 2002). Thus, the peripheral tasks we used (i.e. static location, motion speed, motion direction) would rely on spectral cues more heavily than on binaural cues. The selective deficit in MC's motion direction perception would suggest then, that processing of spectral cues was fine for some perceptual judgments (i.e. static location judgment, motion speed judgment), but impaired for others (motion direction). This suggests that the difference in the acoustic feature to be analysed (spectral vs. binaural) as well as the perceptual attribute that needs to be judged (location vs. motion speed vs. motion direction) have to be considered together when characterizing the deficit we observed in MC. Spectral and binaural cues are processed along separate pathways in the auditory system (e.g. King, Schnupp & Doubell, 2001). Our results suggest that there might also be separate processing of spectral vs. binaural cues for different aspects of auditory spatial perception."

Minor/specific comments:

1) Abstract line 38: I think "compartmentalization" may be too strong a term given the numerous complexities of interpretation (e.g. see above).

To address the reviewer's concern we have replaced this sentence with the following:
"Most importantly, however, our data break new ground by suggesting a division of auditory motion processing in terms of speed and direction and in terms of central and peripheral space."

2) I understand that the bias component of MC's deficit is to over-report clockwise motion. To what extent have the authors investigated the nature of the percept? Assuming it's not a reporting or response bias, does MC rate illusory clockwise motion as more similar to actual clockwise motion than to other motion, for example? I.e. are the errors accompanied by uncertainty or by confident misperception?

Our response to this question is based on observation during testing sessions. During testing, MC's delivery of responses in left or right peripheral conditions did not seem to be different from delivery of responses in central conditions. This would suggest that her errors might possibly have been confident misperceptions. Nonetheless, when we tested MC she had already participated in a number of alternative forced choice studies, and as such had experience giving a response even when she is not sure.

Highlights

- Patient MC has lesions including posterior temporal and parietal cortex
- MC has deficit in perception of sound motion direction in peripheral space
- division of auditory motion processing into speed vs. direction
- division of auditory motion processing into peripheral vs. central

A selective impairment of perception of sound motion direction in peripheral space: A case study

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Running Title: Selective Impairment Spatial Hearing

Abstract

It is still an open question if the auditory system, similar to the visual system, processes auditory motion independently from other aspects of spatial hearing, such as static location. Here, we report psychophysical data from a patient (female, 42 and 44 years old at the time of two testing sessions), who suffered a bilateral occipital infarction over 12 years earlier, and who has extensive damage in the occipital lobe bilaterally, extending into inferior posterior temporal cortex bilaterally and into right parietal cortex. We measured the patient's spatial hearing ability to discriminate static location, detect motion and perceive motion direction in both central (straight ahead), and right and left peripheral auditory space (50 degrees to the left and right of straight ahead). Compared to control subjects, the patient was impaired in her perception of direction of auditory motion in peripheral auditory space, and the deficit was more pronounced on the right side. However, there was no impairment in her perception of the direction of auditory motion in central space. Furthermore, detection of motion and discrimination of static location were normal in both central and peripheral space. The patient also performed normally in a wide battery of non-spatial audiological tests. Our data are consistent with previous neuropsychological and neuroimaging results that link posterior temporal cortex and parietal cortex with the processing of auditory motion. Most importantly, however, our data break new ground by suggesting a division of auditory motion processing in terms of speed and direction and in terms of central and peripheral space.

Keywords: Spatial Hearing, Sound Motion, Parietal Cortex, Occipital Cortex, Lesion, Psychophysics

1. Introduction

Dynamic properties of spatial sounds, such as sound motion, are salient aspects of the acoustic environment. Early on it has been questioned if the auditory system, like the visual system, processes motion independently from static location (e.g. Grantham, 1986). Evidence in favour of such a compartmentalization of the auditory system has been accumulating. For example, neuroimaging suggests that areas in temporal and parietal cortices are more active in the processing of auditory motion as compared to static location (e.g., Baumgart, Gaschler-Markefski, Woldorff, Heinze, & Scheich, 1999; Bremmer et al., 2001; Griffiths, Bench, & Frackowiak, 1994; Griffiths et al., 1998; Hall, Hart, & Johnsrude, 2003; Krumbholz et al., 2005; Lewis, Beauchamp, & DeYoe, 2000; Poirier et al., 2005; Saenz, Lewis, Huth, Fine & Koch, 2008; Warren, Zielinski, Green, Rauschecker, & Griffiths , 2002). Supporting evidence has also been reported using electroencephalography, EEG (Getzmann, 2011; Krumbholz et al., 2007), and transcranial magnetic stimulation, TMS (Lewald et al., 2011). There is additional neuropsychological evidence to suggest cortical specialization for auditory motion processing, such as reports of motion deafness after damage to temporal (Ducommun et al., 2004) or temporal and parietal brain areas (Griffiths et al., 1996; Lewald, Peters, Corballis, & Hausmann, 2009). Of particular relevance to our current report is the study by Lewald et al. (2009), who introduced three cases of hemispherectomy (two left, one right), all of whom showed severely impaired perception of motion direction combined with milder deficits in the perception of static location. Most interestingly, Lewald et al. (2009) also described a case with right anterior temporal lobectomy (case MB), who showed impaired processing of stationary location, whilst his ability to perceive motion direction was entirely normal. They proposed that the processing of stationary location may take place in more anterior parts of the temporal lobe (i.e. Heschl's gyrus, superior, middle and inferior temporal gyri and the temporal pole), whereas the processing of motion may take place in posterior parts of the temporal lobe and/or in the parietal cortex.

In the current study we introduce patient MC, who has bilateral lesions in posterior parts of the temporal lobe and in right parietal cortex (in addition to lesions in the occipital lobe). Thus, she has brain lesions that permit a direct test of the hypothesis that processing of stationary location may take place in more anterior parts of the temporal lobe, whereas processing of motion direction may take place in posterior parts of the temporal lobe and/or in the parietal cortex. Specifically, if the hypothesis put forth by Lewald et al. (2009) is true, MC should show a deficit in the perception of motion direction, but intact perception of stationary location, and in this way the behavioural data observed in MC and MB would form a double-dissociation.

Lewald et al. (2009) used a task in which participants had to judge the direction of motion in right and left peripheral auditory space (i.e. 50 degrees to the left and right of straight ahead), and the location of a stationary sound in central auditory space (i.e. straight ahead). Thus, the nature of the perceptual judgment (i.e. judgment of motion direction vs. judgment of static location) was confounded with the part of auditory space in which the stimulus was presented (i.e. peripheral vs. central). Typically, people perform better when they are tested in central as compared to peripheral space (e.g. Blauert, 1997). Thus, to avoid confounding the nature of the perceptual judgment with the part of auditory space in which the stimulus is presented, we tested MC's ability to perceive motion direction and static location in central as well as right and left peripheral auditory space. In addition, we decided to test not only MC's perception of sound motion direction, but also her processing of sound motion speed (i.e. detection). The reasoning behind the latter manipulation was that for the processing of visual motion it has been suggested that separate mechanisms may be employed for the processing of direction and speed (e.g. Matthews & Qian, 1999; Matthews, Luber, Qian, & Lisanby, 2001), and we wanted to explore if a similar separation might exist in the auditory domain. For example, if sound motion direction was processed separately from sound motion speed, one might observe a deficit in the perception of sound motion direction whilst perception of sound motion speed might be normal, or vice versa. In sum, here we tested perception of static location, motion speed and motion direction in both central and peripheral auditory space. Such a complete set of test has not been conducted previously. To ensure that MC's non-spatial hearing ability was intact, we also conducted a wide array of non-spatial hearing tests.

2. Material and methods

Testing occurred on two separate occasions, approximately two years apart. For the first test occasion, patient MC and two control participants were tested at the University of Western Ontario, and the remaining five control participants were tested at Durham University. For the second test occasion MC was tested at her home, and seven control participants were tested at Durham University. Consent was obtained according to the Declaration of Helsinki. All testing procedures were approved by the ethics board at Durham University and the University of Western Ontario. Participants gave written informed consent prior to testing. The consent form was read to participants, and the location on the form to sign was indicated through tactile and visual markers. Participants received 30 $CA/hr or 18 £/hr for their participation.

2.1. Participants

2.1.1. Case Description MC

At times of testing patient MC (female, right-handed) was 42 (and 44) years old. She had suffered a bilateral occipital/temporal infarction approximately 12 (and 14) years prior to testing. Prior to her incident, MC had worked as a secretary at a hospital eye clinic. She is intelligent, high-functioning, highly motivated, and very personable, upbeat, and cooperative.

Although MC has no awareness of stationary targets anywhere in her visual field, she does detect moving targets in some portions of her visual field, consistent with Riddoch phenomenon (Riddoch, 1917). Following her incident, MC developed strabismus, with concomitant right exotropia and hypertropia (that is, her right eye deviates outward and upward). As such (and combined with a complete absence of the occipital poles, where foveal vision is represented), MC has difficulties directing and maintaining fixation. One attempt at perimetry five years after her incident failed and another attempt mentioned in her clinical records (date unspecified) indicated residual motion perception across the entire visual field. On our first test occasion, MC's visual fields were plotted using kinetic Goldmann perimetry (stimulus target size V4e) while her gaze was visually monitored. MC failed to detect static targets anywhere within the visual field. Results of tests using moving targets are shown in Figure 1. She had spared detection of moving targets in her upper left visual field at eccentricities ranging between 10 – 60 degrees of visual angle, and there was also an island of preserved detection in the lower right visual field. Although the data from the two eyes do not overlap perfectly due to impaired fixation because of her lack of central vision, nevertheless, spared motion detection occurs consistently in both the upper left and lower right visual quadrants.

Figure 2-4 show pictures from a high resolution structural MRI scan (MPRAGE - Magnetization Prepared RApid Gradient Echo) of MC's brain taken three days after psychophysical testing on the first occasion for the current study. Data in Figures 2-4 are shown in coronal, sagittal and transverse, views respectively. Data are shown in native space (with the horizontal "ACPC" plane intersecting the anterior and posterior commissures) rather than standard stereotaxic space to minimize distortion. It is evident that at time of testing MC had extensive lesions in the occipital lobe, sparing only a small section of tissue located around anterior calcarine sulcus bilaterally. With regard to the temporal lobe, it appears that the lateral surface is intact, incl. Heschl's gyrus, planum temporale, superior, middle and inferior temporal gyri and the temporal pole. Damage is evident, however, bilaterally in the inferior part of the posterior temporal lobes. Specifically, in the left hemisphere the posterior 90-100% of lateral occipitotemporal gyrus, posterior 90-100% medial occipitotemporal gyrus, 100% parahippocampal and 100% of lingual gyrus are absent. In the right hemisphere parahippocampal gyrus is still present, the posterior 70-80% of lateral occipitotemporal gyrus, posterior 90-100% medial occipitotemporal gyrus, and 90-100% of lingual gyrus are absent. With regard to the parietal lobe, it appears that lesions are located in right parietal cortex. Specifically, lesions stretch along the whole length of the right intraparietal sulcus, sparing only portions of angular gyrus and portions of the inferior and superior parietal lobules that border the postcentral sulcus. Lesions in the occipital lobe are extensive. In the left hemisphere only a small anterior portion of lateral-occipital gyrus and parts of the cuneus bordering the parieto-occipital fissure and calcarine/parieto-occipital junction are spared. In the right hemisphere only a small anterior portion of lateral-occipital gyrus, and small parts of lingual gyrus right below calcarine and bordering the calcarine/parieto-occipital junction are spared (note that we also listed lingual gyrus lesions when referring to the temporal lobe, but the remaining elements are so close to occipital lobe structures that we mention them here).

Functional MRI testing for other projects revealed intact processing for many functional areas in zones where the anatomical image appeared normal (Culham, Witt, Valyear, Dutton, & Goodale, 2008). Importantly, this included the middle temporal motion complex (MT+) which has been implicated in visual motion processing (Tootell et al., 1995). Specifically, contrasts between moving and stationary checkerboards revealed reliable fMRI activation at the junction of the inferior temporal and lateral occipital sulci, close to the stereotaxic locations for MT+ in control participants. On our second test occasion we therefore measured MC's ability to detect vertical sine wave gratings that moved either left- or rightwards and that varied in motion speed, luminance contrast, and spatial frequency. We also tested her ability to detect and discriminate rotational (cw/ccw at +/-90°/s) and translatory (L/R at +/-22°/s) visual motion using random dot pattern (100% coherence, 100% contrast). Testing was done using a Samsung SyncMaster 2333 Monitor **(**510 mm(H) x 287 mm(V); 1920 (H) x 1080 (V) at 60Hz; viewing distance 57cm; luminance of black 0.2 cd/m^2) and MacMini5.1 (2.3 GHz Intel core i5; 2GB RAM) running MacOS X Lion 10.7.4 and VPixx (VPixx

Technologies Inc.; Quebec, Canada). We used stimuli whose circular aperture subtended 28°/visual angle and we encouraged MC to direct her gaze at the centre of the display. The results are shown in Figure 5. It is evident that MC's ability to detect visual vertical sine wave gratings depends on speed, contrast and spatial frequency. That is, she detects stimuli with higher accuracy when speed and contrast are higher, and when SF is lower. Performance of control subjects (n=2) is 100% correct throughout, indicating that MCs performance is impaired in particular in low contrast, low speed conditions. MCs ability to detect or discriminate specific types of visual motion in random dot patterns (left or rightwards translation, cw or ccw rotation) is near perfect, similar to performance of control subjects (n=2) who are 100% correct in all conditions. With regard to MC's auditory abilities, there was no record of anomalies, in verbal or non-verbal aspects of her auditory cognition. MC and her family reported that pure tone audiometric threshold testing had been performed in the past, but that the results of these tests had not revealed any anomalies either. MC and her family reported to not have noticed any problems in terms of her auditory abilities.

2.1.2. Control Participants

Eleven gender- and age-matched neurologically intact control participants took part. Control participants consisted of academic and administrative staff from our department and members of the general public. Educational background was variable (ranging from high school to PhD). Seven participated in the first testing occasion (age range 40-51, mean 41.8, SD 7.7), and seven (three of who had also participated in the first testing occasion) in the second (age range 32-54, mean 43.7, SD 8.2). They all reported normal hearing and vision.

2.2. Non-Spatial Audiological Tests

To confirm that MC's basic auditory function was intact we performed a range of measurements, including visual otoscopic examination of ear canals and tympanic membranes, tympanometry to determine middle ear status, behavioural audiometry to determine pure tone audiometric thresholds, distortion product otoacoustic emission (DPOAE) measurements to assess outer hair cell function, measurement of DPOAE inhibition elicited by contralateral noise to assess the brainstem's auditory olivocochlear efferent system, and measurement of click evoked auditory brainstem responses (ABR) to assess synchronicity in the auditory brainstem.

2.3. Spatial Sound Stimuli

Sounds were computer generated (44.1 kHz, 16 bit) using the SuperCollider audio programming language. Sounds were 0.5-10k Hz bandpass filtered white noise with a 40-Hz sinusoidal amplitude modulation (between zero and maximum amplitude) and 1-s duration. HRTF filter coefficients were derived from a set of measurements conducted with a Knowles Electronic Mannequin for Acoustic Research (KEMAR) under anechoic conditions (Gardner & Martin, 1995). The stimuli we used were similar to those used in a previous study investigating auditory perception of static location and motion (Lewald et al., 2009). We generated static sounds in the horizontal meridian for locations from -86° to +86° in 0.5° steps. We generated horizontal motion sounds moving either clockwise or counterclockwise. The speed ranged from 80°/s to 0°/s in steps of 2°/s. Moving stimuli were generated separately for three testing locations (+50°, -50°, 0°). Thus, a sound moving at 80°/s clockwise at reference location +50°, would start at +10° and stop at +90°, whereas a sound moving at 80°/s clockwise at reference location 0°, would start at -40°, and stop at +40°. Subjects were presented with sounds using Sensimetrics S14 in-ear headphones (Sensimetrics, Malden, MA, USA), connected via a Dayton DTA-1 digital amplifier (Dayton, Springboro, Ohio, USA) to a PC (Intel Integrated Audio 2.0). These headphones have a reliable but non-flat frequency response. Thus, prior to listening, sounds were equalized using filters provided by the headphone manufacturer. On the first testing occasion (adaptive testing), participants were free to adjust sound volume to their own comfort level. Importantly, the same volume setting was then used for all tasks. On the second occasion sound volume was fixed across all participants at about 60 dB SPL.

2.4. Psychophysical Procedure

To measure auditory perception thresholds on the first testing occasion we employed an adaptive staircase method, which revealed a deficit in motion direction perception in two repeated tests (see results). Adaptive staircase methods have the advantage that they are efficient, but a disadvantage is that they may not yield accurate results if underlying assumptions (e.g. that a threshold exists) are violated (Treutwein, 1995). As such, to validate the results of the first testing occasion, we testing MC again on a second occasion using the method of constant stimuli, which does not achieve a threshold if none exists (e.g., if responses are random) .

Software used to conduct testing was programmed using Psychophysics Toolbox 3.08 (Brainard, 1997) and Matlab (R2009a, The Mathworks, Natick, MA, USA). On the first testing occasion, a separate adaptive staircase procedure was run for each task (static location, motion speed, motion direction) and test location (0°, +50°, -50°). For patient MC the order of test locations and tasks was 0°, -50°, +50° (static location), 0°, +50°, -50° (motion speed), 0°, -50°, +50° (motion direction, adaptive test 1), +50°, -50° (motion direction, adaptive test 2). Note that for MC we ran two adaptive motion direction tests for locations -50 and +50. The second test had been prompted by her performance in the first test (see results), i.e. we wanted to run more trials to double-check her performance. For four of the control subjects, the order was the same as for patient MC, with the exception that they did not participate in a second motion direction test. For three control subjects the order was 0°, +50°, -50° (static location), 0°, -50°, +50° (motion speed), 0°, +50°, -50° (motion direction). The different tasks were run on separate days. On the second testing occasion, we re-tested perception of motion direction using the method of constant stimuli. Testing sessions took place on a single day, and were split into sub-blocks by testing location. For patient MC the order of test locations was 0°, -50°, +50°, 0°, +50°, -50°. For four of the control subjects, the order was the same as for patient MC, whilst the for three control subjects the order was 0°, +50°, -50°, 0°, -50°, +50°. All testing was conducted in a quiet room. Throughout testing participants were seated, held their head still facing straight ahead, and kept their eyes closed.

2.4.1. Static Location – Adaptive Staircase

To determine thresholds for processing static location we employed a 2-Interval-2-Alternative-Forced-Choice adaptive staircase method. The participant’s task on every trial was to listen to a pair of sounds with 800 ms of silence in between, and to determine whether a test sound was located clockwise or counterclockwise from a reference sound. Presentation was sequential, such that the reference sound was always presented first and the test sound second. To make sure that participants understood the task, alternative descriptions and response options were provided, for example right vs. left for the central testing location, or towards the periphery (e.g. on an arc from the participant’s straight ahead towards a more eccentric location) or towards the centre (e.g. on an arc from the participant’s side towards their straight ahead). Participants were free to perform as many practice trials as they wanted. Testing only commenced once it was clear that the participant understood what was asked from them and that they were confident with the response options. Participants could listen to each sound pair as often as they wished. The experimenter keyed the participant’s response into the computer. To minimize the possibility of procedural bias, two intertwined staircases were used that approached the reference position clockwise or counterclockwise, each starting from a 36° angular difference from the reference position. Presentation order of staircases was pseudo-random such that one staircase would not run for more than 4 consecutive trials. The angular difference between test and reference on each trial was determined adaptively. In the first two trials we used the stochastic approximation by Robbins-Monro (Robbins & Monro, 1951):

$$x_{n+1} = x_n - \frac{c}{n\ (z_n - \varphi)}$$

where *n* is the number of the current trial, *x* the value of the stimulus, and *c* the initial step size (set at 36°), φ is the probability of responding in a correct or incorrect way with respect to the corresponding staircase (0.5 in our paradigm) and *z* defines if the response was correct (1) or incorrect (0), referring to the corresponding staircase (e.g., 'clockwise' is correct for the clockwise- and incorrect for the counterclockwise-starting staircase). For subsequent trials we used the accelerated stochastic approximation by Kesten (1958):

$$x_{n+1} = x_n - \frac{c}{(2+m)(z_n - \varphi)}$$

This additionally includes *m* for the number of changes in the response category, i.e., *m* increased by one when the response switched from left to right, or vice versa, in one staircase. The test was terminated after 20 trials per staircase (= 40 total). For each reference position the test took approximately 15 minutes to complete.

Sounds were made for only a subset of locations in 0.5° steps. However, test values for threshold determination were computed on a continuous scale (see equations above). The testing procedure was therefore adapted as follows: On each trial, the requested test value was computed by the computer. If the requested sound was available, then that sound was played. If the requested sound was not available, the sound closest to the requested was played. The requested test value for the next trial was computed based on the played test value and the participant's response.

2.4.2. Motion Speed – Adaptive Staircase

To determine participants' ability to process motion speed we employed a 2-Interval-2-Alternative-Forced-Choice adaptive staircase method. The participant's task on every trial was to listen to a pair of sounds with 800 ms of silence in between, and to determine if either the first or the second sound was moving (i.e. 2AFC motion detection task). Participants were free to perform as many practice trials as they wanted. Testing only commenced once it was clear that the participant understood what was asked from them and that they were confident with the response options. Presentation was such that one of the two sounds was always a stationary reference sound, and the other a moving test sound, and presentation order was random. Participants could listen to each sound pair as often as they wished. The experimenter keyed the participant's response into the computer. To minimize the possibility of procedural bias, two intertwined staircases were used in which the test stimulus moved either clockwise or counterclockwise, each starting from either a +80 or -80 °/s motion angle. Presentation order of staircases was pseudo-random such that one staircase would not run for more than 4 consecutive trials. The speed difference between test and reference on each trial was determined adaptively, using the algorithm described above. The only difference was that the initial step size c was set to 80°/s.

Sounds had been made for only a subset of motion angles in steps of 2°/s. However, test values for threshold determination were computed on a continuous scale (see equations above). The testing procedure was therefore adapted just as for static location perception.

Before the experiment started, the experimenter explained the task and procedure to the participant. The participant was told that it might become increasingly more difficult to determine which of the two sounds was moving, and that this was a consequence of the procedure used. Participants were told that if they were uncertain about which of the two sounds was moving, they should respond with their "best guess".

2.4.3. Motion Direction – Adaptive Staircase

To determine motion direction perception thresholds adaptively we employed a 1-Interval-2-Alternative-Forced-Choice adaptive staircase method. The participant's task on every trial was to listen to a single sound, and to determine if it moved either clockwise or counterclockwise. To make sure that participants understood the task, alternative descriptions and response options were provided, for example right vs. left moving for the central testing location, or towards the periphery

(e.g. sound moving on an arc from the participant's straight ahead towards a more eccentric location) or towards centre (e.g. sound moving on an arc from the participant's side towards their straight ahead). Participants were free to perform as many practice trials as they wanted. Testing only commenced once it was clear that the participant understood what was asked from them and that they were confident with the response options. Participants could listen to each sound as often as they wished. The experimenter keyed the participant's response into the computer. To minimize the possibility of procedural bias, two intertwined staircases were used in which the test stimulus moved either clockwise or counterclockwise, each starting from either a motion angle of +80 or -80 °/s, respectively. Presentation order of staircases was pseudo-random such that one staircase would not run for more than 4 consecutive trials. The speed on each trial was determined adaptively, using the algorithm described above. Initial step size c was set to 40°/s.
General testing procedures were otherwise identical to those in the other tasks.

We want to emphasize that the sound stimuli that were used in the motion direction task were identical to those used in the motion speed task (incl. sound volume). However, the two tasks required participants to judge different aspects of the stimulus (i.e. speed vs. direction of motion). It follows, that differences in performance between the two tasks must be due to differences in perceptual processing of the sound stimulus, rather than to differences in the physical stimulus itself.

2.4.4. Motion Direction– Constant Stimuli

The participant's task on every trial was to listen to a single sound, and to determine if it moved either clockwise or counterclockwise. At -50° and +50° testing locations they listened to stimuli moving -80, -60, -40, -20, 0, +20, +40, +60 and +80° per second. At 0° testing location they additionally listened to stimuli moving -10 and +10° per second. Control participants listened to 12 stimuli per condition (108 total for each peripheral location, 132 total for the centre location). To make sure that we had enough trials to measure any potential deficit in MC, she listened to 20 stimuli per condition (180 total for each peripheral location, 220 total for the centre location). Participants could listen to each sound as often as they wished. The experimenter keyed the participant's response into the computer. Presentation order of stimuli was pseudo-random such that stimuli of each type could not occur on more than two consecutive trials.

Before the experiment started, the experimenter explained the task and procedure to the participant. Just as for the adaptive procedure, to make sure that participants understood the task, alternative descriptions and response options were provided as well, participants were free to perform as many practice trials as they wanted, and testing only commenced once it was clear that the participant understood what was asked from them and that they were confident with the response options. The participant was told that it might be difficult to determine in which direction the sound was moving on some trials. Participants were told that if they were uncertain about the direction in which the sound was moving, they should respond with their "best guess".

2.5. Psychophysical Data Analysis

Psychophysical performance was measured by fitting psychometric curves to the data and then using these to compute bias and threshold for each. Curves were fitted separately for each participant, test location and task. For static location and motion direction data we fitted two-parameter sigmoid curves of the form $F = \frac{1}{1+\exp\left(-\frac{x-a}{b}\right)}$ to data for each reference position separately. To compute bias, we determined the point on the curve where the probability to judge a stimulus as 'clockwise' was 0.5. To compute thresholds we first determined those points on the curve where the probability to judge a stimulus as clockwise was either 0.25 or 0.75. We then computed the average of the absolute threshold values. For speed detection data we fitted two-parameter curves of the type $F = 1 - \exp\left(-\left(\frac{x}{a}\right)^{b}\right)$ to data for each reference position separately. Responses for clockwise and counterclockwise movement angles were collapsed for this analysis, and data for individual participants were corrected for guessing. For the speed experiment we determined thresholds only, because a stationary reference stimulus had been used. To compute thresholds we determined the point on the curve where the probability to judge the stimulus as moving was 0.66. Psychophysical data (bias and thresholds) obtained for patient MC were compared to those obtained for the control group using t-tests developed for single case studies (Crawford & Garthwaite, 2002).

3. Results

3.1. Non-Spatial Audiological Tests

MC’s performance in all non-spatial audiological tests was within the limits of normative samples. The part we consider diagnostic of brain stem function are DPOAE inhibition and ABRs. Importantly, DPOAE inhibition and all aspects of ABRs are normal, except for the inter-aural latency difference for ABR wave III, which was larger than normal in MC (0.33 ms versus 0.17 ms). However, this could be due to asymmetry in the volume conductor (the electrical circuit followed by neural currents) since large portions of MC’s brain are missing, and lesions are not perfectly symmetric between left and right hemisphere. A detailed summary of all test results is available in Supplementary Report S1.

3.2. Motion Direction

Figure 6 shows the results of motion direction perception tests. Top panels show data obtained using method of constant stimuli used to fit psychometric curves. Data from control participants are shown in black, data from MC are shown in red. Bottom panels show bias and threshold data obtained from psychometric curves to either data from constant stimulus methods, or adaptive methods (MC’s results for adaptive tests 1 and 2 are plotted separately). Group data are visualized using boxplots. Data from MC are plotted separately using circles, with the exception of testing location +50 constant stimuli, because we could not obtain a fit of sigmoidal psychometric curves for these data. Note that for MC’s data for motion direction at +50 testing location for constant stimuli, we not only tried a two parameter sigmoid, but also a four parameter sigmoid $F = c + \frac{d-c}{1+\exp\left(-\frac{x-a}{b}\right)}$. Nonetheless, we were unable to determine a threshold value. Boxplots are robust non-parametric indicators of central tendency and spread. As such, they allow visual comparison between data from MC and the control group.

From the raw data (constant stimuli) it is evident that for all participants the probability to judge a stimulus as moving clockwise increases as the movement angle changes from counterclockwise to clockwise. For the 0 degree test location it is also evident that MC's performance agrees well with those of the control subjects, i.e. the red curve is contained within the group of black curves. In contrast, for both the -50 and +50 test location MC's performance deviates from the performance of the control participants. In particular, she has a general tendency to perceive sound motion in peripheral space as being clockwise. On the left side this appears to lead to a general shift of her overall response curve, whereas on the right side this leads to her incorrectly perceiving in particular fast counterclockwise movements (-60°/s and -40°/s). This finding is mirrored in the bias and threshold data (bottom panels). Specifically, for the method of constant stimuli MC's bias is outside the range of the control participants for the -50 location (t(6) = -3.402; p<.014), and it cannot be computed for the +50 location because psychometric curves cannot be fitted to these data due to her impaired performance. In contrast, for the 0 degree test location MC's bias is not different from that observed in the control group (t(6)=-.05;p=0.962). A similar picture emerges analysing bias data obtained using the adaptive method. Specifically, MC's bias is outside the range of the control participants for both the -50 and +50 test locations in both her first and second testing session (*-50, test 1*: t(6) = 13.7; p<.001; *-50, test 2*: t(6) = -5.5; p=.002; *+50, test* 1: t(6) = -23.5; p<.001; *+50, test 2*: t(6) = -14.87; p=.002), whilst for the 0 degree test location MC's bias is not different from that observed in the control group (t(6)=-1.2;p=0.104). Notably, in peripheral space, four out of five 'biases' are counterclockwise (compare boxplots for -50 and +50 testing locations in Figure 6). The bias is the movement angle for which MC is equally likely to perceive clockwise or counterclockwise movement. Thus, a counterclockwise bias indicates that MC tends to judge sound movement as being clockwise.

In regard to thresholds, using the method of constant stimuli, MC's threshold is not different from the controls at either the -50 test location (t(6)=-0.559; p= 0.597) or the 0 test location (t(6) = 0.944; p = 0.382). In contrast, it cannot be computed for the +50 degree test location, because of her severely impaired performance which does not allow us to fit psychometric curves. Again, a similar picture emerges based on threshold data obtained using the adaptive method. Specifically, MC's threshold is significantly different from that of the control group for the +50 test location on both her first and second testing session (*+50 test 1*: t(6)=31.04;p<.001; *+50 test 2*: t(6)=7.44;p<.001) , but does not differ at the -50 test location (*-50 test 1*: (t(6)=0.48;p=.65; *-50 test 2*: t(6)=2.31;p=.06) or the 0 degree test location (t(6)=-1.17;p=0.287). On average the control group had a bias close to zero at all test locations (adaptive tests: arithmetic mean: -50=-0.25, 0=0.3, +50 = 1.11; constant stimuli: arithmetic mean: -50=0.84 , 0=0.95), except for the +50 test location with constant stimuli where bias was 4.54. Yet, this bias was not significantly different from zero (t(6)=1.668;p=.146; Wilcoxon signed rank test: z(6)=-1.521;p=.128). Threshold values in peripheral space exceeded those in central space (adaptive tests: arithmetic mean: -50=7.7, 0=5.6, +50=9.1; constant stimuli: arithmetic mean: -50=8.1, 0=2.57, +50 = 7.3). The same pattern of results is also evident in the non-parametric boxplots in Figure 6. It is expected that psychophysical thresholds should be lower in central as compared to peripheral space (e.g. Blauert, 1997). Furthermore, the threshold values we observe in our control subjects at the +50 and -50 test locations agree well with those reported previously for neurologically intact participants with similar stimuli and experimental tasks (Lewald et al., 2009). Lewald et al. (2009) did not test performance in central auditory space, however.

In summary, the data suggest that MC's perception of motion direction is within normal range in central auditory space, but outside of normal range in peripheral auditory space, with a graded impairment from left to right space. i.e. in left peripheral space only her bias differs significantly from controls whilst her threshold does not, whilst in right peripheral space both her bias and threshold are outside the normal range. Since her bias and threshold exceed those observed in the control group, her difference in performance represents impairment rather than an improvement. MC herself spontaneously reported that she could clearly hear that the sound was moving, but that she could not make out in which direction the motion went.

3.3. Motion Speed Detection

Figure 7 left panel shows the results of the motion speed detection test with respect to thresholds. Data are shown in boxplots in the same format as threshold data for motion direction in Figure 6. Since the reference stimulus was a stationary stimulus we only determined thresholds for these data. It is evident that for all testing locations MC's performance agrees well with those of the control subjects. In fact, MC's threshold is not significantly different from that of the control group for any of the three test locations (*-50*: t(6)=-0.427;p=.684; *0*: t(6)=0.238; p=0.82; *+50*: t(6)=0.844;p=.431).

On average, the control group's average threshold values in peripheral space exceeded those in central space (arithmetic mean: -50=11.6, 0=10.7, +50=10.8). This is expected from the literature (e.g. Blauert, 1997). In summary, the data suggest that MC's ability to process motion speed is within normal range in both peripheral and central space.

We want to emphasize once more that the sound stimuli that were used in the speed task were identical to those used in the motion direction task. Thus, the differences in performance that we observe between the two tasks must be due to differences in perceptual processing of the sound stimulus, rather than to physical differences in the stimulus itself.

3.4. Static Location

Figure 7 right panels show the results of the static location discrimination test with respect to bias and thresholds. Data are shown in boxplots in the same format as bias and threshold data for motion direction in Figure 6. It is evident that for all testing locations MC's performance agrees well with those of the control subjects. In fact, MC's bias or threshold are not significantly different from those of the control group for any of the three test locations (bias: *-50*: t(6)=-2.37;p=.056; *0*: t(6)=-1.332 ; p=.231; *+50*: t(6)=-1.217;p=.269; threshold: *-50*: t(6)=-1.572, p=.167; *0*: t(6)=.288;p=.783; *+50*: t(6)=-.78, p=.465). On average the control group had a bias close to zero at all test locations (arithmetic mean -50= 0.003, 0 =0.2, +50 =0.2), and threshold values in peripheral space exceeded those in central space (arithmetic mean -50=2.8, 0 =1.6, +50 =2.5). This is similar to the pattern of results we observed in the motion direction and motion speed tasks, and expected from the literature (e.g. Blauert, 1997). In summary, the data suggest that MC's perception of static location is within normal range in both peripheral and central space.

4. Discussion

MC shows a highly selective impairment for the processing of sound motion direction in peripheral auditory space, which is more pronounced on the right side (i.e. on the right side both bias and threshold are outside normal range, whereas on the left side it is only her bias). Interestingly, on neither side of space is her deficit due to her responses being random, but rather she has a general tendency to perceive movements as being clockwise. On the left side this leads to a general shift of her overall response curve, whereas on the right side this leads to her perceiving in particular fast counterclockwise movements (-60°/s and -40°/s) as moving clockwise. We argue that her impairment represents an inability to correctly perceive motion direction, caused by damage to posterior temporal and parietal cortices. The reason that we argue that her deficit is caused by damage to mechanisms specific for processing direction of auditory movement as opposed for example to mechanisms for static spatial analysis is that her performance in tasks that required static spatial analysis was normal. Thus, the most parsimonious explanation of our results, also considering her lesion sites as well as previous literature on this topic, is that she has damage to mechanisms that are specific for auditory movement.

Her normal performance in the static location discrimination task rules out the possibility that her deficit might be caused by an intellectual deficit, or impairments in arousal, or (spatial) attention. Specifically, due to her extensive brain lesions one might argue that the deficit in the motion direction task might be due to an inability to correctly process the geometry underlying the response, to understand the instructions, or to attend to sound in specific parts of space. As laid out in the method section, we took care to frame response options in various ways as well as via practice trials so that all participants, including MC, were confident about the instructions and response options. Most importantly, however, MC showed no impairment in performing the static location task in peripheral space, which required her to categorize locations as clockwise or counterclockwise in left and right space just as the motion direction task required her to judge direction of movement. This rules out the possibility that her deficit might be caused by a general intellectual deficit or impaired arousal/attention. Furthermore, MC's normal performance in the speed and the static location task, as well as her normal performance in our non-spatial auditory test battery (compare section 3.1), also rule out potential low-level explanations (such as the possibility of subcortical damage).

In static location conditions participants listened to two successive stationary sounds that could differ in location, and participants may have perceived illusory motion in those conditions. The gap between two successive sounds was 800 ms, which is too long for an illusion of movement to occur under the testing conditions we employed (Burtt, 1917; Strybel, Manligas, Chan & Perrott, 1990). Also, none of the participants commented on a percept of illusory motion. Importantly, even if participants experienced illusory motion it would - if anything - make the static location task more similar to the motion direction task. Yet, we still found a qualitative difference in performance for MC between these two tasks. This supports our interpretation that these two tasks measured different aspects of auditory cognition with the most likely difference being that one task tapped participants’ ability to process location, whereas the other tapped their ability to process motion direction.

Our stimuli had been designed based on a previous report about auditory motion direction perception (Lewald et al., 2009). Stimuli in central conditions crossed the midline, whereas stimuli in peripheral conditions did not. There is the possibility that our observation of a peripheral deficit in sound motion perception is due to the fact that stimuli used for the assessment of the peripheral part of space were limited to one hemispace, whereas stimuli used for the assessment of the central field crossed the midline. Notably, however, MCs deficit is more pronounced in right as compared to left peripheral space, suggesting that crossing of the midline (or not) may not be the sole variable determining performance.

One thing to also consider in this context is the likelihood that different acoustic cues would be used for different tasks. Specifically, spatial processing (including motion processing) in peripheral space is likely to depend more on the processing of spectral (versus binaural) cues than spatial processing in central space, which is likely to rely more on binaural cues. This is because binaural cues (i.e. ITD, ILD) do not change as rapidly with azimuth for peripheral targets as they do for central targets, in particular across the midline (e.g. King, Schnupp & Doubell, 2001; MacPherson & Middlebrooks, 2002). Thus, the peripheral tasks we used (i.e. static location, motion speed, motion direction) would rely on spectral cues more heavily than on binaural cues. The selective deficit in MC’s motion direction perception would suggest then, that processing of spectral cues was fine for some perceptual judgments (i.e. static location judgment, motion speed judgment), but impaired for others (motion direction). This suggests that the difference in the acoustic feature to be analysed (spectral vs. binaural) as well as the perceptual attribute that needs to be judged (location vs. motion speed vs. motion direction) have to be considered together when characterizing the deficit we observed in MC. Spectral and binaural cues are processed along separate pathways in the auditory system (e.g. King, Schnupp & Doubell, 2001). Our results suggest that there might also be separate processing of spectral vs. binaural cues for different aspects of auditory spatial perception.

4.1. Brain Areas involved in Processing of Sound Motion Direction

Previous literature based on results from neuroimaging, EEG, TMS, and neuropsychological investigations suggests a specialization for the processing of sound motion in posterior temporal and/or parietal cortex (e.g., Baumgart et al., 1999; Bremmer et al., 2001; Ducommun et al., 2004; Getzmann, 2011; Griffiths et al., 1994; Griffiths et al., 1996; Griffiths et al., 1998; Hall et al., 2003; Krumbholz et al., 2005; 2007; Lewald et al., 2009; 2011; Lewis et al., 2000; Poirier et al., 2005; Saenz et al., 2008; Warren et al., 2002). Our findings are consistent with this previous literature. As laid out in the introduction, of particular relevance to the current results is the study by Lewald et al. (2009). In this study, patients with hemispherectomy showed severely impaired perception of motion direction, and milder deficits in the perception of static location. In contrast, a case with right anterior lobectomy (case MB), showed impaired processing of stationary location, whilst his ability to perceive motion direction was entirely normal. Lewald et al. (2009) hypothesized that the processing of stationary location may take place in more anterior parts of the temporal lobe, whereas the processing of motion may take place in posterior parts of the temporal lobe and/or in the parietal cortex.

Interestingly, MC shows lesions in those areas highlighted for processing of motion direction by Lewald et al. (2009): temporal lobe areas posterior to the planum temporale and parietal cortex. Furthermore, the results with regard to static location and peripheral perception of motion direction observed in MC form a double-dissociation with those observed in MB. Taken together, these two cases provide general support for the idea that motion direction in peripheral space and static location are processed independently from one another in posterior temporal and parietal cortices, respectively.

Notably, our data allow us to further delineate the areas involved. Specifically, as reported by Lewald et al. (2009) patients with hemispherectomy (i.e. missing both temporal and parietal cortex unilaterally) also have deficits in determining motion direction, similar to MC. MB on the other hand, who has intact parietal and posterior temporal cortex, has intact motion discrimination in peripheral space. With respect to MC, large parts of posterior temporal cortex were still intact, whilst her lesions in right parietal cortex are extensive. In sum, considering the results from MB, MC and subjects with hemispherectomy together suggests that the parietal lesions are more relevant for the observed deficits in perception of motion direction in MC.

Consistent with this, our data also support the idea put forward by Lewald et al (2009) that the planum temporale is not critically involved in processing of motion direction. Specifically, MC's planum temporale is intact bilaterally, but she nevertheless shows a deficit in the motion direction task. Conversely, case MB had lesions in the planum temporale, but had no deficit in processing motion direction. Functional neuroimaging results have implicated the planum temporale in processing of auditory motion (e.g. Krumbholz et al., 2005), but these studies have exclusively focused on detection of motion rather than perception of motion direction, so that this pattern of results is not inconsistent with the results obtained in MC or MB.

Most importantly, we want to emphasize that the overall pattern of results we found in MC paints a picture of spatial hearing that is much more complex than static location vs. motion, but that also considers motion speed and direction, as well as central and peripheral space. In particular, since we conducted tests in both central and peripheral space, and for both sound speed and direction, we found that MC's ability to perceive motion direction in central auditory space was normal, despite her impairment in peripheral space. In addition, her ability to perceive motion speed in both central and peripheral space was normal. This is the first time that such a complete set of spatial hearing tests has been conducted in such a patient. In contrast, MB's ability to perform static location discrimination in the periphery as well as his ability to perform the speed task remains unknown. Future investigations are needed to investigate the neural substrates of the various spatial auditory abilities outlined here, and their relationships among one another.

4.2. Lateralization

MCs deficit was more pronounced on the right side of space. This seems counterintuitive as her lesions, in particular in parietal cortex, are more extensive in the right hemisphere, so that one may expect a more pronounced deficit in the left side of space. Nonetheless, patients with hemispherectomy, despite having a lesion in only one hemisphere, showed a profound deficit in both sides of space (Lewald et al., 2009), showing that strict contra-laterality does not apply for processing of auditory motion. Furthermore, neurologically intact subjects have superior performance in processing of motion direction in left as compared to right peripheral auditory space (Hirnstein et al., 2013). It is possible that this general 'left-side advantage' is the reason for MC's better performance in left space, despite her lesions in right parietal cortex.

4.3. Relation to Visual Processing

MC's visual abilities are quite different from her auditory abilities. Specifically, she has a profound deficit in perceiving static visual stimuli, but a remarkably preserved ability to detect and discriminate visual motion. Detailed testing of motion perception in her visual field is complicated by the fact that she has difficulties fixating visual targets (compare also visual field maps in Figure 1 which show lack of sensitivity to stimuli in her central field of vision). As mentioned in the case description, functional neuroimaging has also revealed activity in a region of her brain consistent with the location of visual motion area MT+ in sighted control subjects. In sum, at this stage both behavioural data and neuroimaging suggest that in the visual modality MC (and other patients with Riddoch phenomenon, Riddoch, 1917) may be the conceptual 'opposite' of cases described with akinetopsia (i.e. the inability to perceive visual motion), first described by Zihl and colleagues (Zihl et al, 1983; 1991), and later investigated in subsections of the visual field by Plant and others (Plant et al., 1993; Plant & Nakayama; 1993). Yet, difficulties in obtaining detailed measurements of MC's ability to detect and discriminate motion or static stimuli in subsections of her visual fields (because of her difficulties maintaining fixation) make direct comparisons to those previous cases difficult.

Based on data at hand, MC shows deficits both in her visual and her auditory abilities, but due to the challenge in measuring her visual abilities in detail it is difficult to assess detailed correspondence and/or dissociations across modalities. In their first assessment of a patient with akinetopsia, Zihl et al. (1983) commented on the fact that the patient had no problems detecting and judging direction of tactile and auditory motion. Yet, due to lack of detailed measurements in non-visual modalities a comparison is difficult also in this case. Nonetheless, occipital brain areas (possibly visual motion area MT+) have also been implicated in auditory motion processing (e.g., Poirier et al., 2005) and future work should aim to identify possible correspondences and/or dissociations across modalities. It has been shown that lack of vision due to damage to the retina or optic nerve can affect spatial auditory processing. The patterns of results that have been observed in people who are totally blind from peripheral causes, however, are quite different from those that we observe in MC in the current report. For example, people who are totally blind from peripheral causes typically show an improvement in processing location of static sounds in peripheral space (e.g. Voss et al., 2004), or sound motion direction (Lewald et al., 2013) as compared to sighted people. In contrast, MC's performance was not different from controls for the static location task, and even impaired as compared to controls in the motion direction task. Thus, her performance is quite different from performance expected for people who are blind from peripheral causes. It is important to keep in mind, however, that MC does have residual visual abilities as well as lesions in brain areas that may be involved in neuroplastic changes arising in response to blindness from peripheral causes (for reviews see, e.g., Bavelier and Neville, 2002; Burton, 2003; Merabet and Pascual-Leone, 2010; Noppeney, 2007; Röder and Rösler, 2004). As a result, it is difficult to compare MC's performance to performance of participants who are totally blind from peripheral causes.

5. Conclusion

The overall pattern of results we found in MC paints a picture of spatial hearing that is much more complex than previously assumed, and which not only differentiates between static location vs.

motion, but that also differentiates between detection of motion speed and direction, and between central and peripheral space. Previous studies have not considered or investigated these distinctions, but they provide a fruitful avenue for further research into the organization of auditory spatial processing and its neural substrates.

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Figure Captions

Figure 1 – Visual field maps for MC obtained 12 years after her incident using manual kinetic Goldmann perimetry (stimulus target size V4e).

Figure 2 – Coronal views of structural MRI scan of MC's brain taken within one week of testing. Data are shown in native (ACPC) space in neurological convention (left-is-left). Coordinates represent deviation from the AC point in mm.

Figure 3 – Sagittal views of structural MRI scan of MC's brain taken within one week of testing. Data are shown in native (ACPC) space. Coordinates represent deviation from the centre of the ACPC coordinate system in mm. Negative x coordinate values correspond to the left hemisphere.

Figure 4 – Transverse views of structural MRI scan of MC's brain taken within one week of testing. Data are shown in native (ACPC) space in neurological convention (left-is-left). Coordinates represent deviation from the ACPC plane in mm.

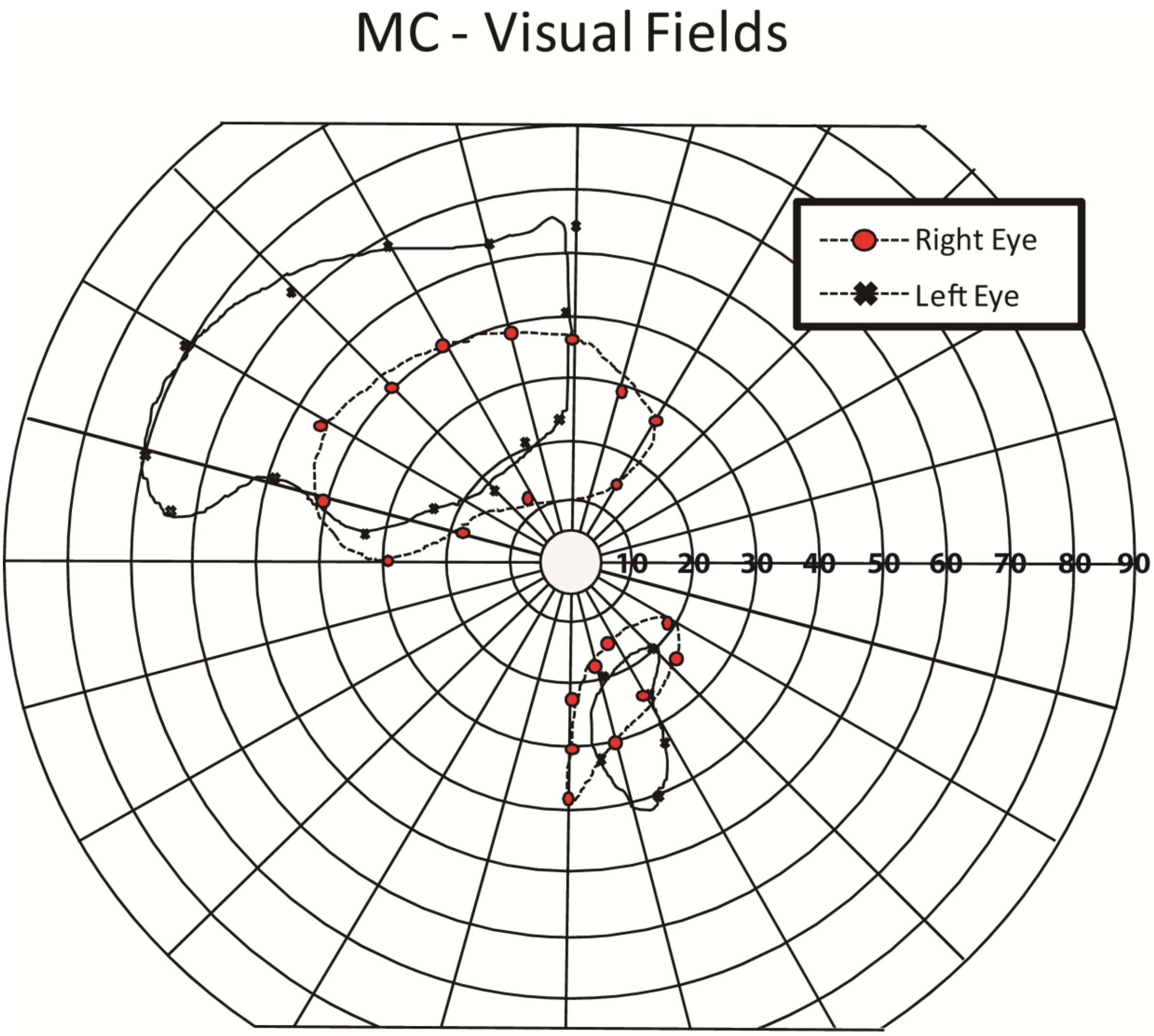
Figure 5 – Results of experiments measuring MCs ability to perceive visual motion. **(A-D) Visual detection of vertical sine wave gratings as a function of contrast, speed and spatial frequency.** On each trial participants were presented with two 2-s intervals, one containing a visual stimulus varying in contrast, speed and spatial frequency, the remaining blank. Interval onset and offset were indicated by masking flashes. The task was to identify which interval contained the visual stimulus (1^{st} or 2^{nd}). Shown is percentage correct (out of 12) for each condition. Data for MC are in black, for

control participants (n=2) in red. Red lines overlap because control participants were 100% correct in all conditions. **(E) Visual detection of rotating and horizontally moving random dot patterns**. On each trial participants were presented with a moving (rotation or horizontal translation) or stationary stimulus and their task was to identify the stimulus (moving or stationary). Shown is percentage correct (out of 40) for each condition. Control participants (n=2) were both 100% correct. **(F) Visual discrimination of rotating and horizontally moving random dot patterns**. On each trial participants were presented with a moving stimulus (rotation or horizontal translation) and their task was to identify the direction of motion (cw/ccw or L/R). Shown is percentage correct (out of 20) for each condition. Control participants (n=2) were both 100% correct.

Figure 6 - Results of auditory motion direction perception tests. Top panels show data from tests using the method of constant stimuli to fit psychometric curves. Data from control participants are shown in black, data from MC are shown in red. Bottom panels show bias and threshold data obtained from fitting psychometric curves for constant stimuli and adaptive methods. Data from control participants are visualized using boxplots, with lower and upper box margins corresponding to the 25th and 75th percentile, respectively, and whisker length corresponding to 1.5 * the interquartile range. This corresponds to approximately +/- 2.7 standard deviations and 99.3 % data coverage if the data were normally distributed. Data from MC are plotted separately (circles), also for adaptive test 1 and 2. As described in the main text, we ran two adaptive motion direction tests for MC for locations -50 and +50. Adaptive test 2 had been prompted by her performance in adaptive test 1, i.e. we wanted to run more trials to double-check her performance. Data for MC for constant stimuli are not plotted for the +50 testing location for constant stimuli as we could not fit psychometric curves for MC due to the shape of the data curve and consequentially, lack of fit for a sigmoidal psychometric curve. Even fitting a four parameter sigmoid curve did not enable us to determine threshold values. Significant differences between MC and control participant's data were

determined using t-test adapted for single case studies (Crawford & Garthwaite, 2002). Significance (two-tailed) is indicated with asterisks. * p<.05, ** p<.01, *** p< .001

Figure 7 - Results of motion speed and static location tests. Panels show bias (except for speed data as bias cannot be computed for this task) and threshold data obtained from fitting psychometric curves. Data from control participants are visualized using boxplots in the same format as in Fig.6. Data from MC are plotted separately (circles). Significant differences between MC and control participant's data were determined using t-test adapted for single case studies (Crawford & Garthwaite, 2002). No significant differences were found.



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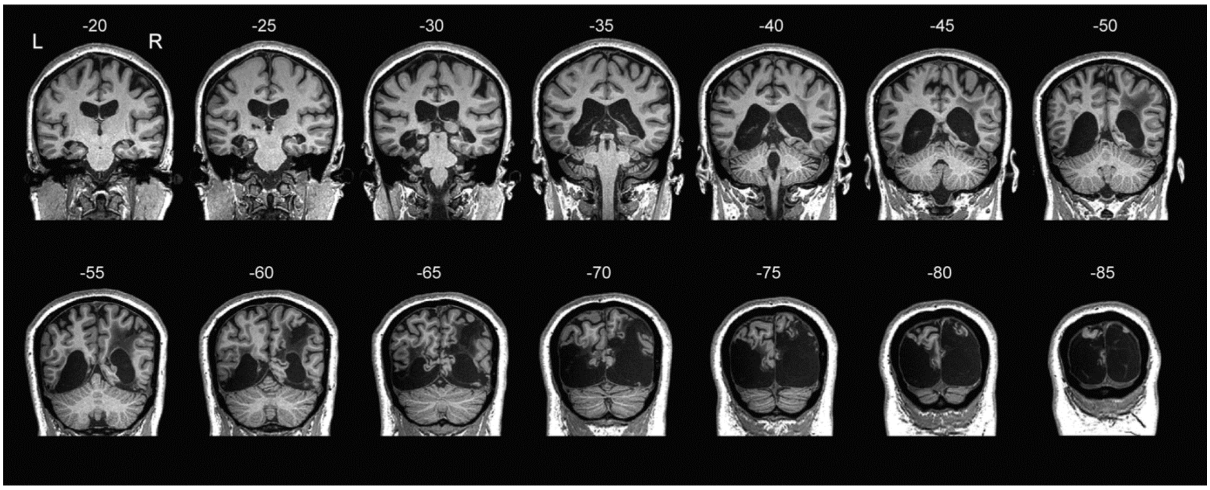


Figure 2

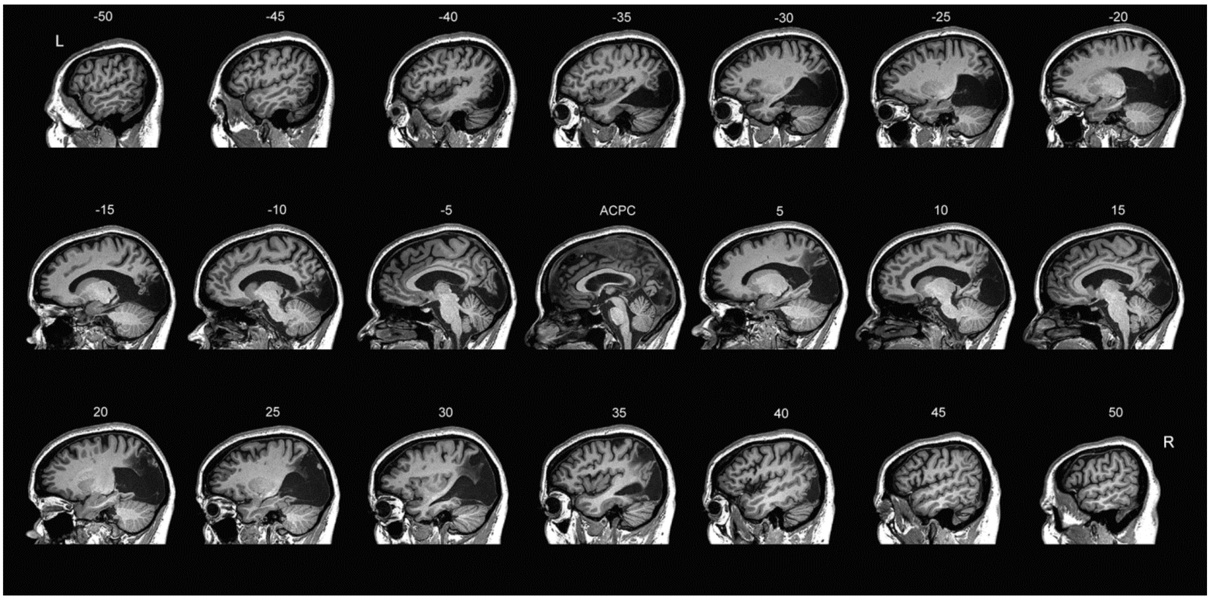
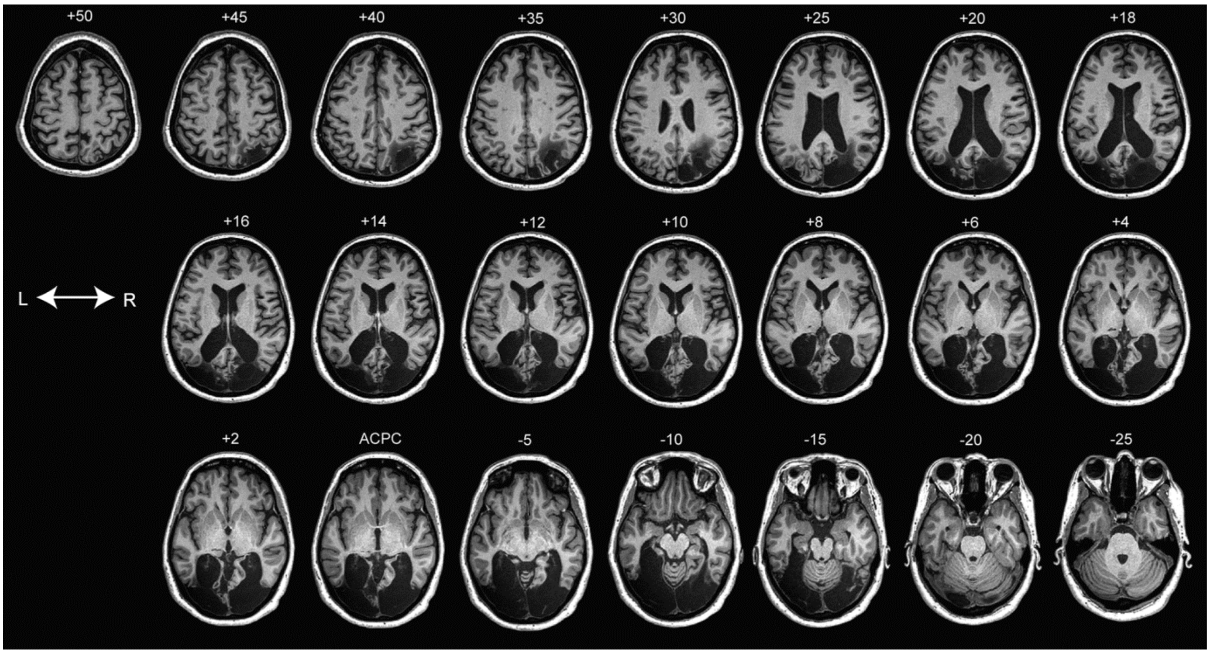


Figure 3



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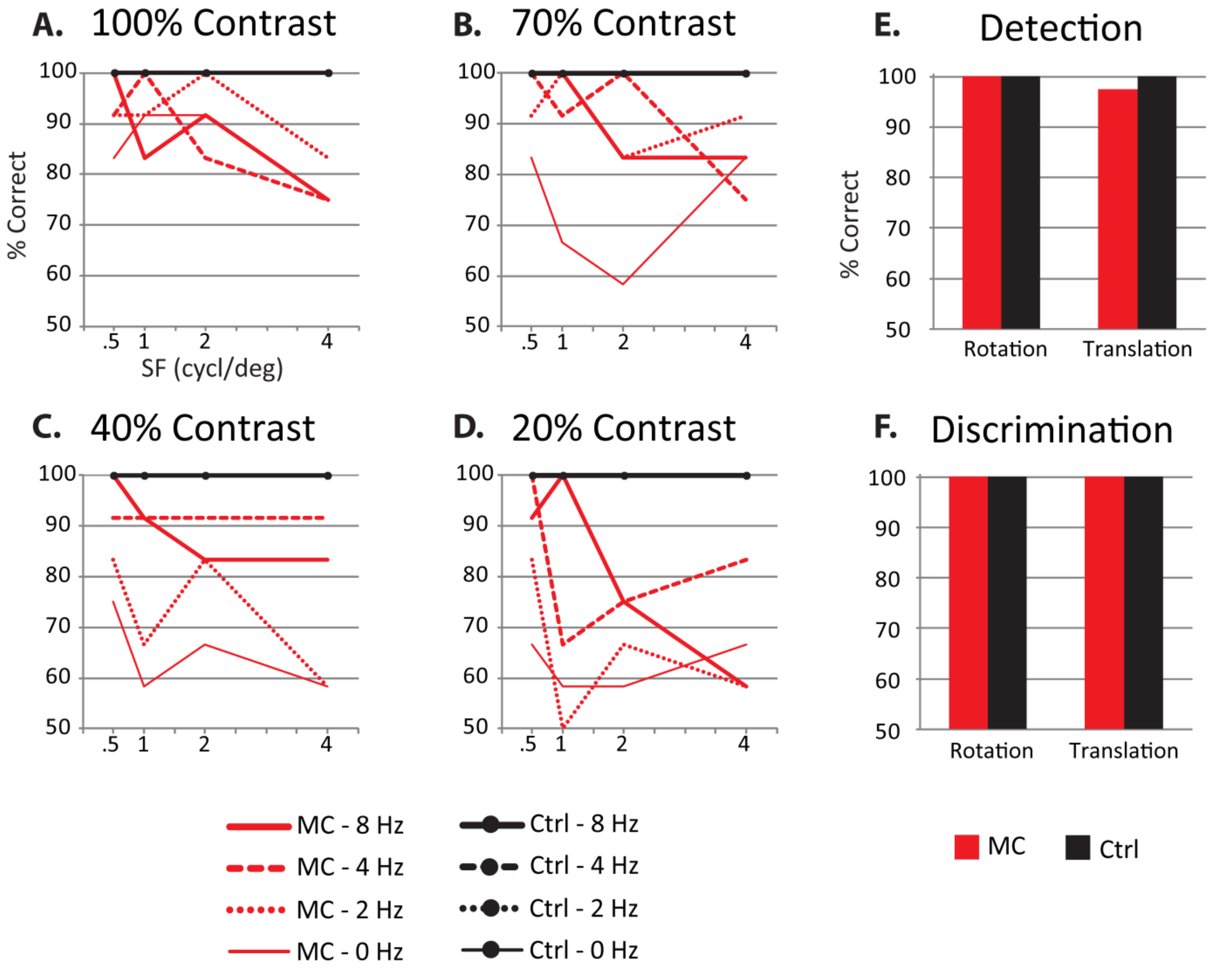
A. 100% Contrast
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C. 40% Contrast
D. 20% Contrast
E. Detection
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2
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Rotation
Translation
MC - 8 Hz
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MC - 2 Hz
MC - 0 Hz
Ctrl - 8 Hz
Ctrl - 4 Hz
Ctrl - 2 Hz
Ctrl - 0 Hz
MC
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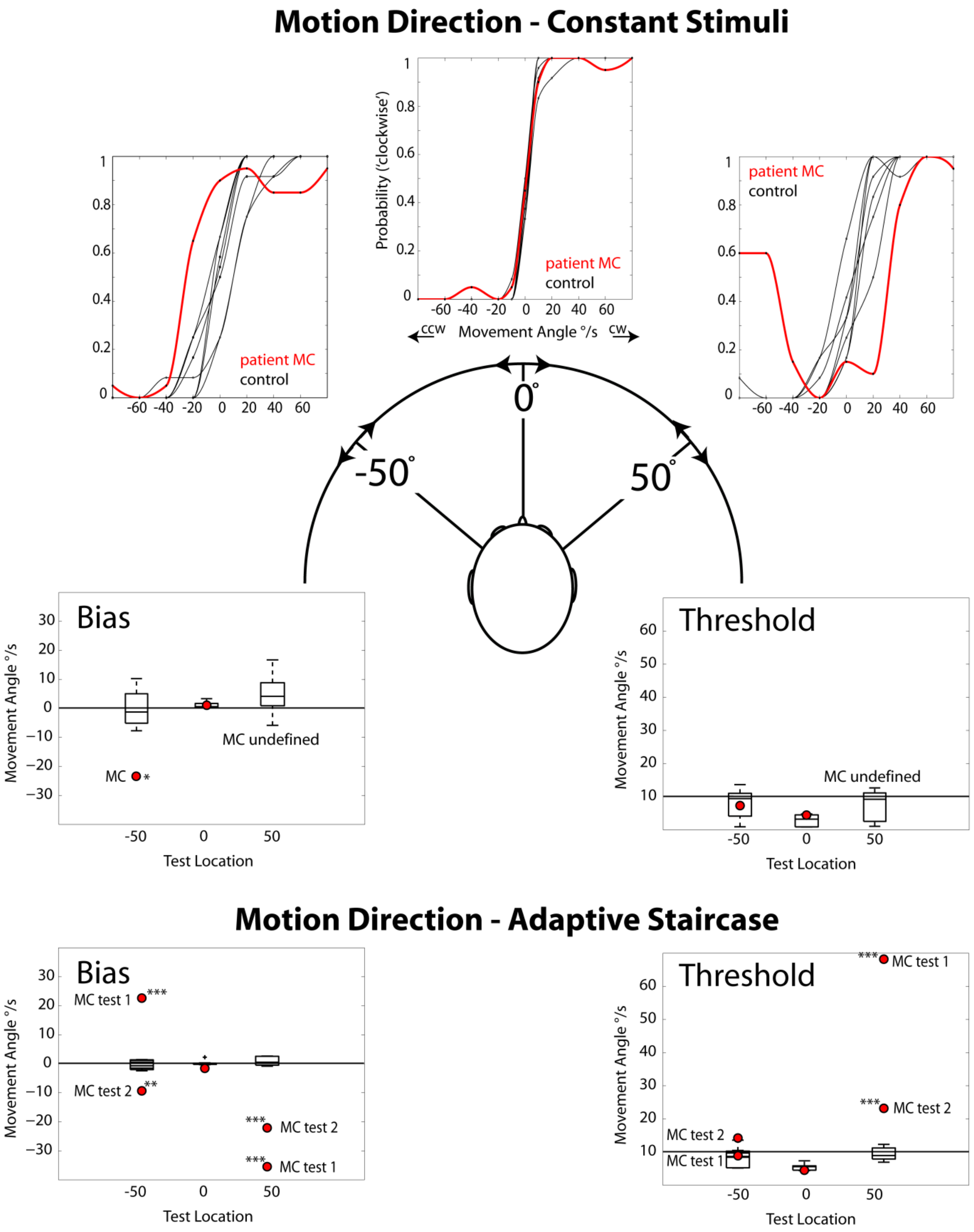
Figure 5


Motion Direction - Constant Stimuli
Probability ('clockwise')
Movement Angle °/s
CCW
CW
patient MC
control
0°
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Bias
Movement Angle °/s
MC undefined
MC *
Test Location
Threshold
MC undefined
Motion Direction - Adaptive Staircase
MC test 1 ***
MC test 2 **
*** MC test 2
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MC test 2
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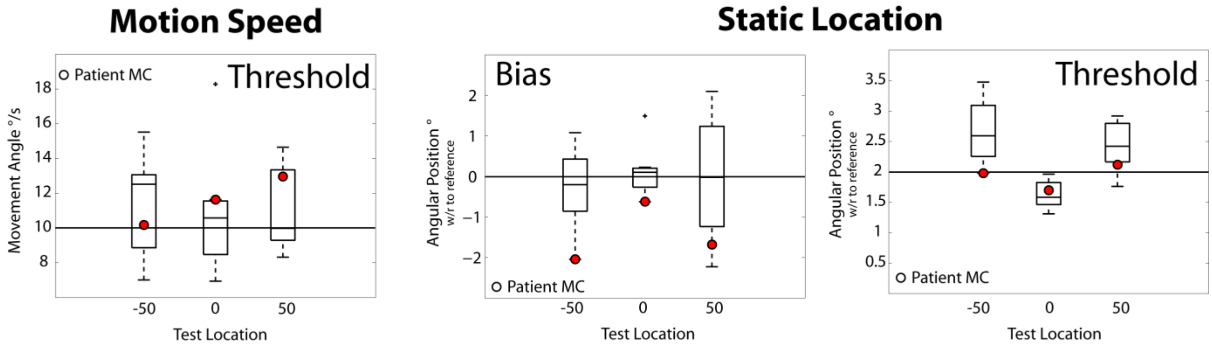
Figure 6


Motion Speed
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Test Location
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Patient MC
-50
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Test Location
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Patient MC
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Test Location

Figure 7

Figure 1

Click here to download high resolution image

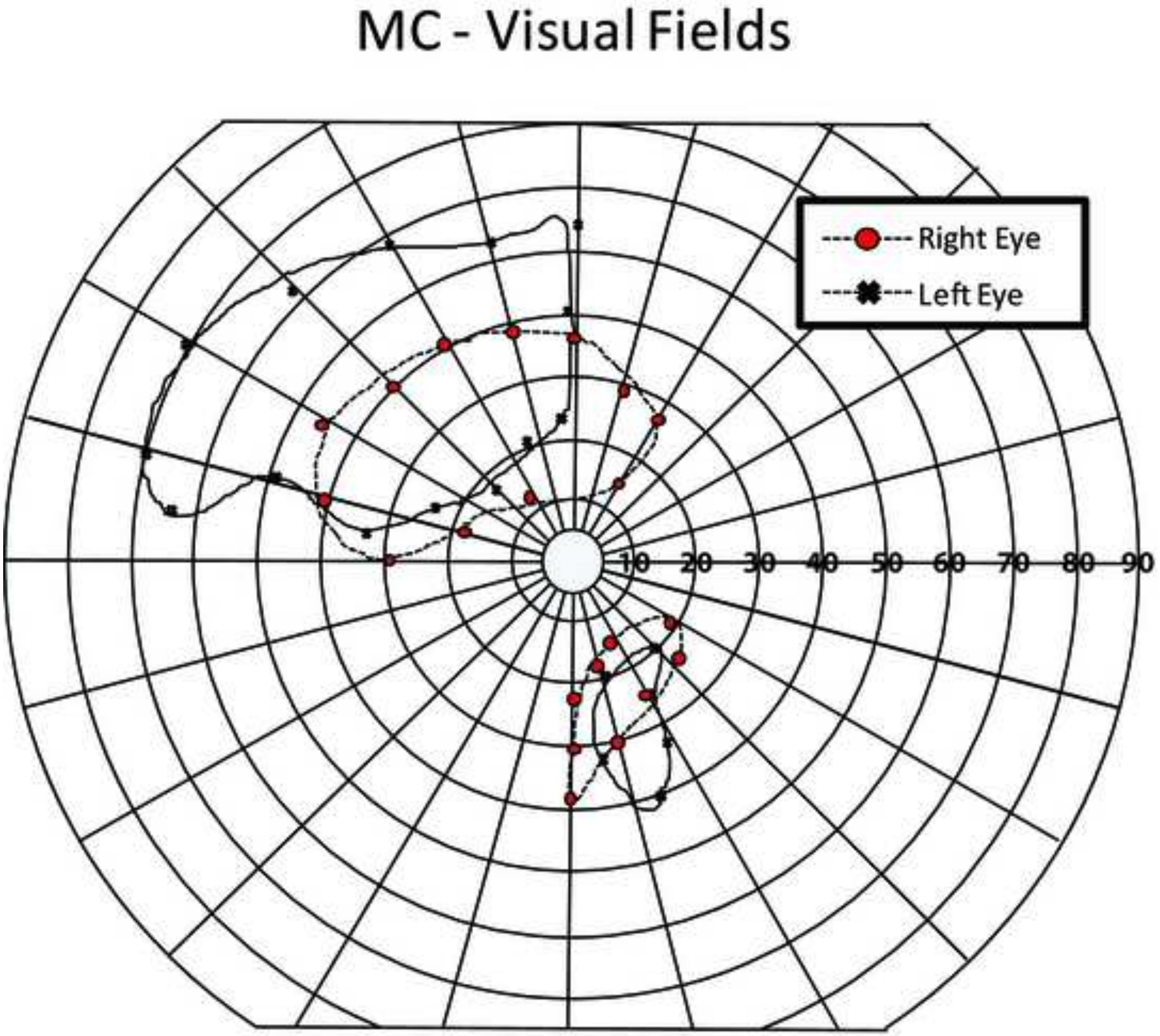

Figure 2

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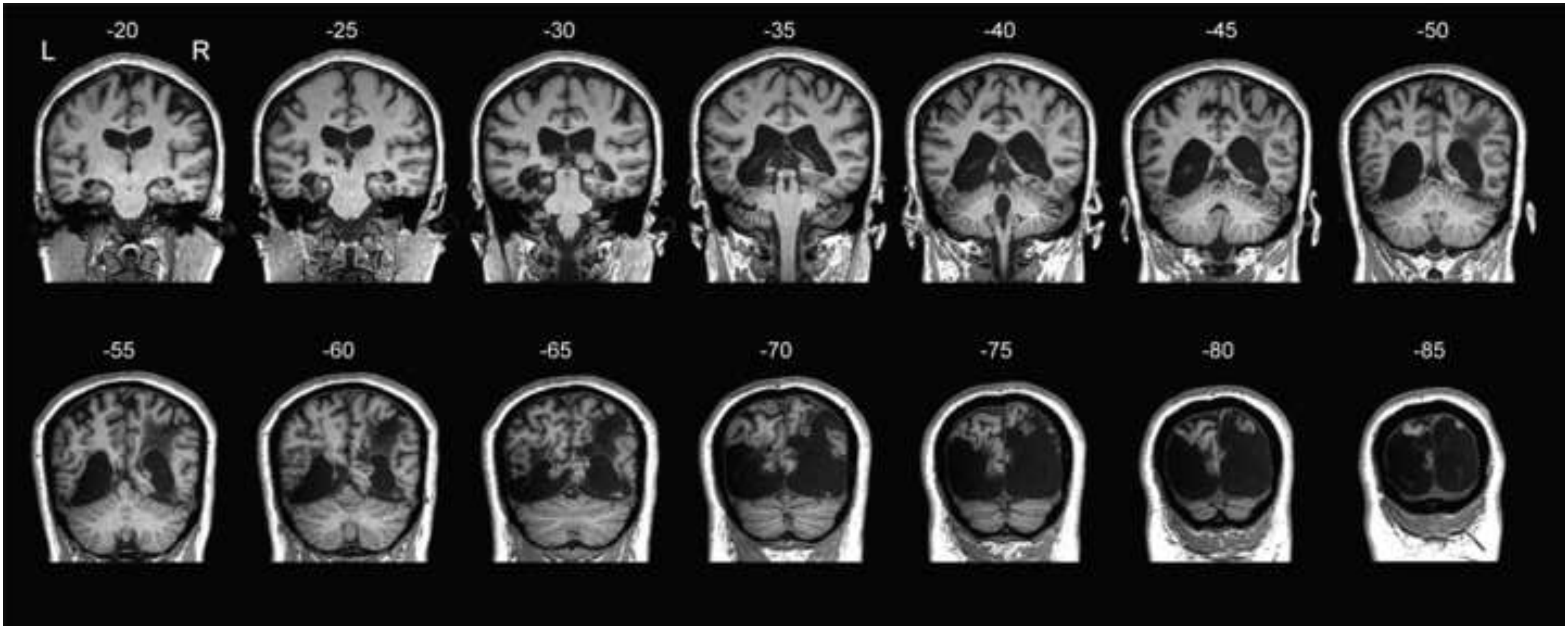

Figure 3

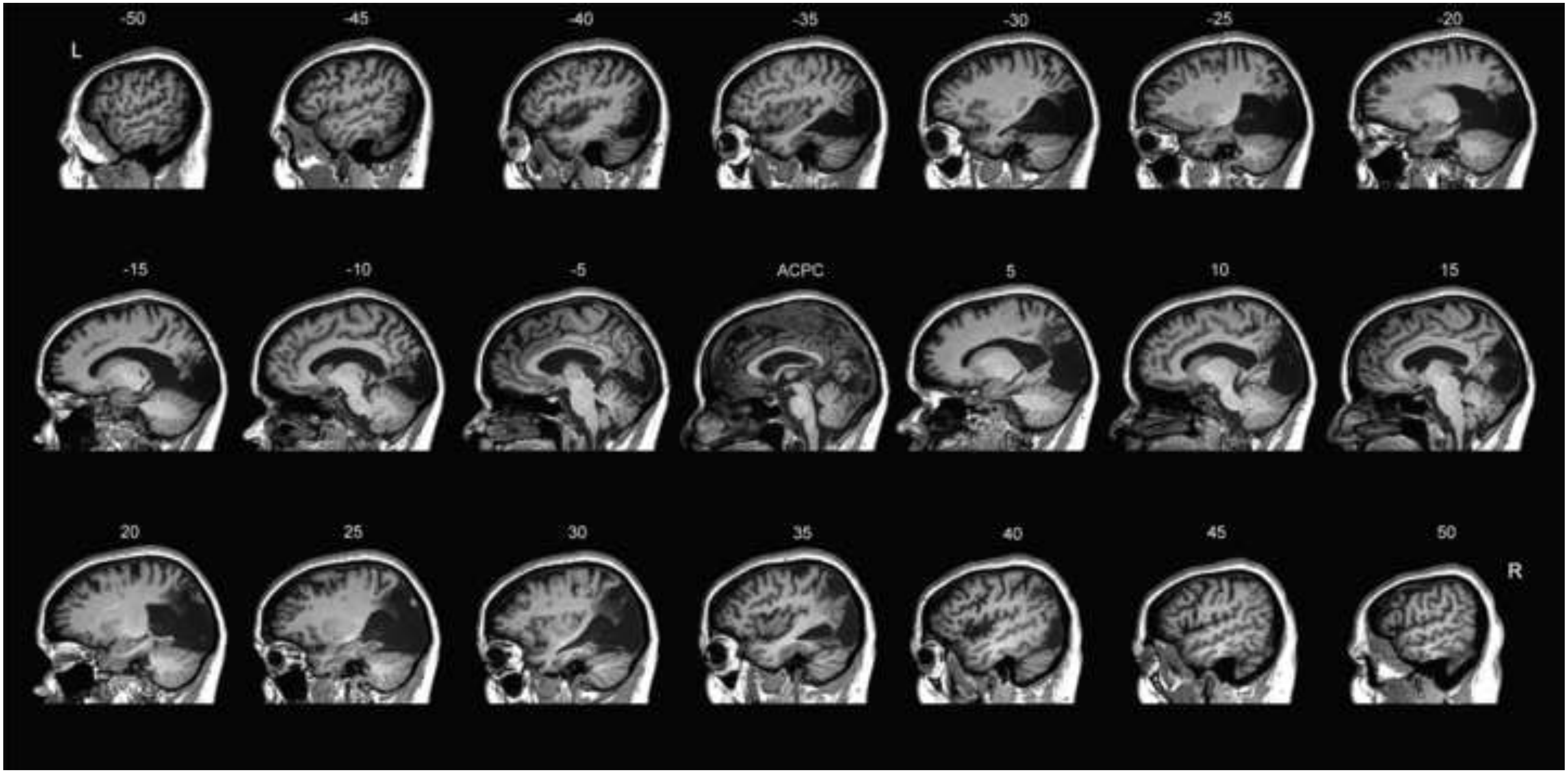

Figure 4

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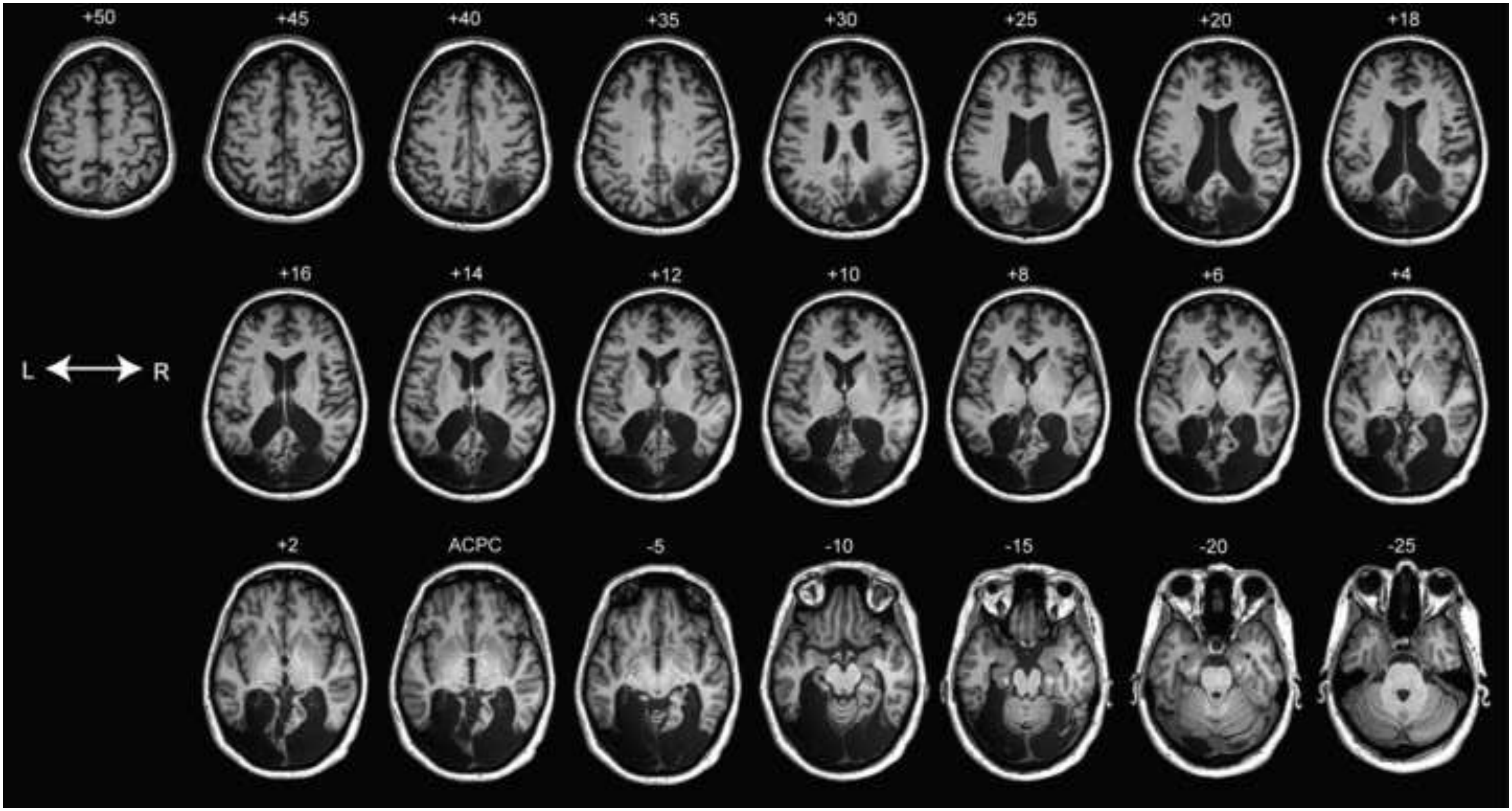

Figure 5

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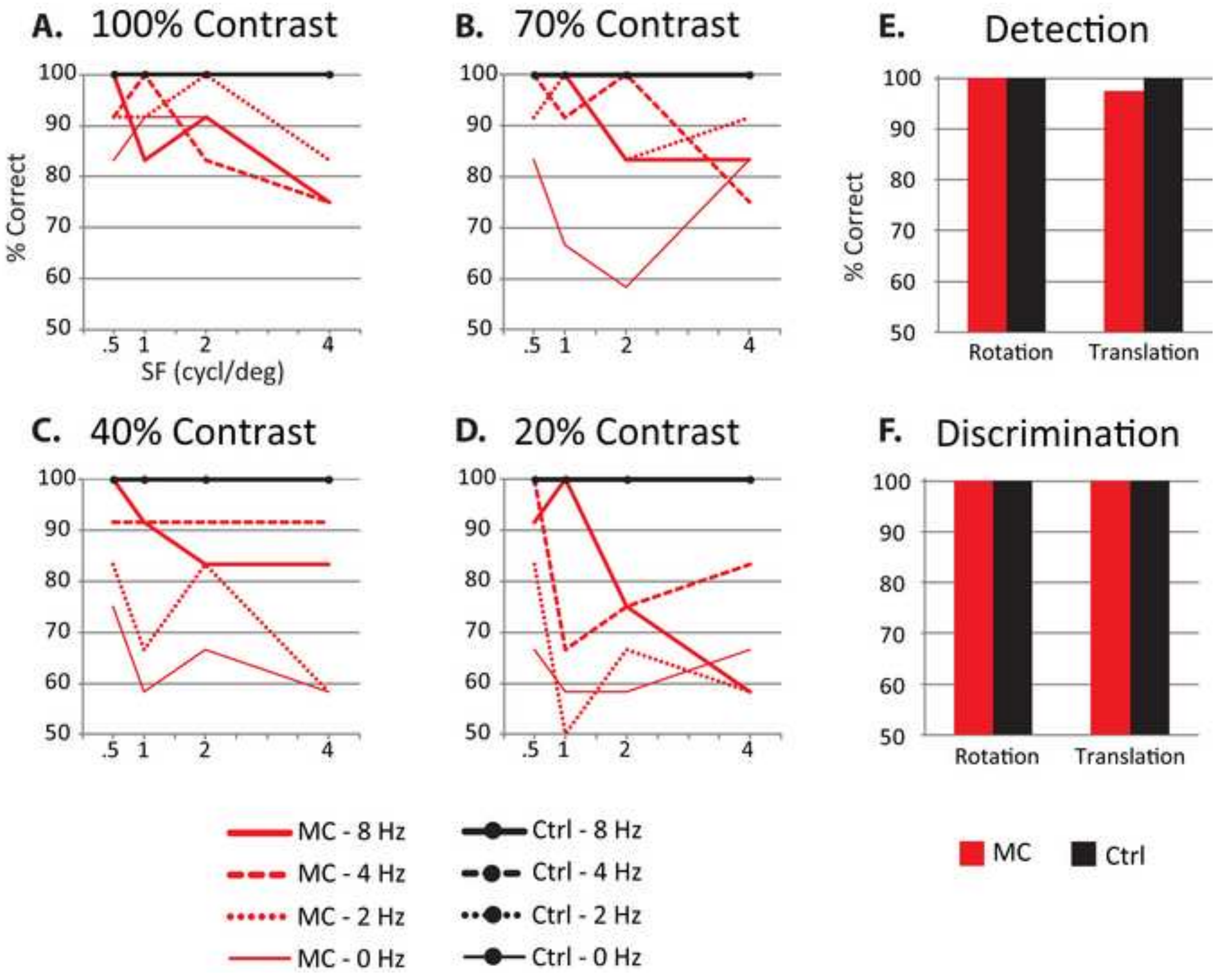

Figure 6

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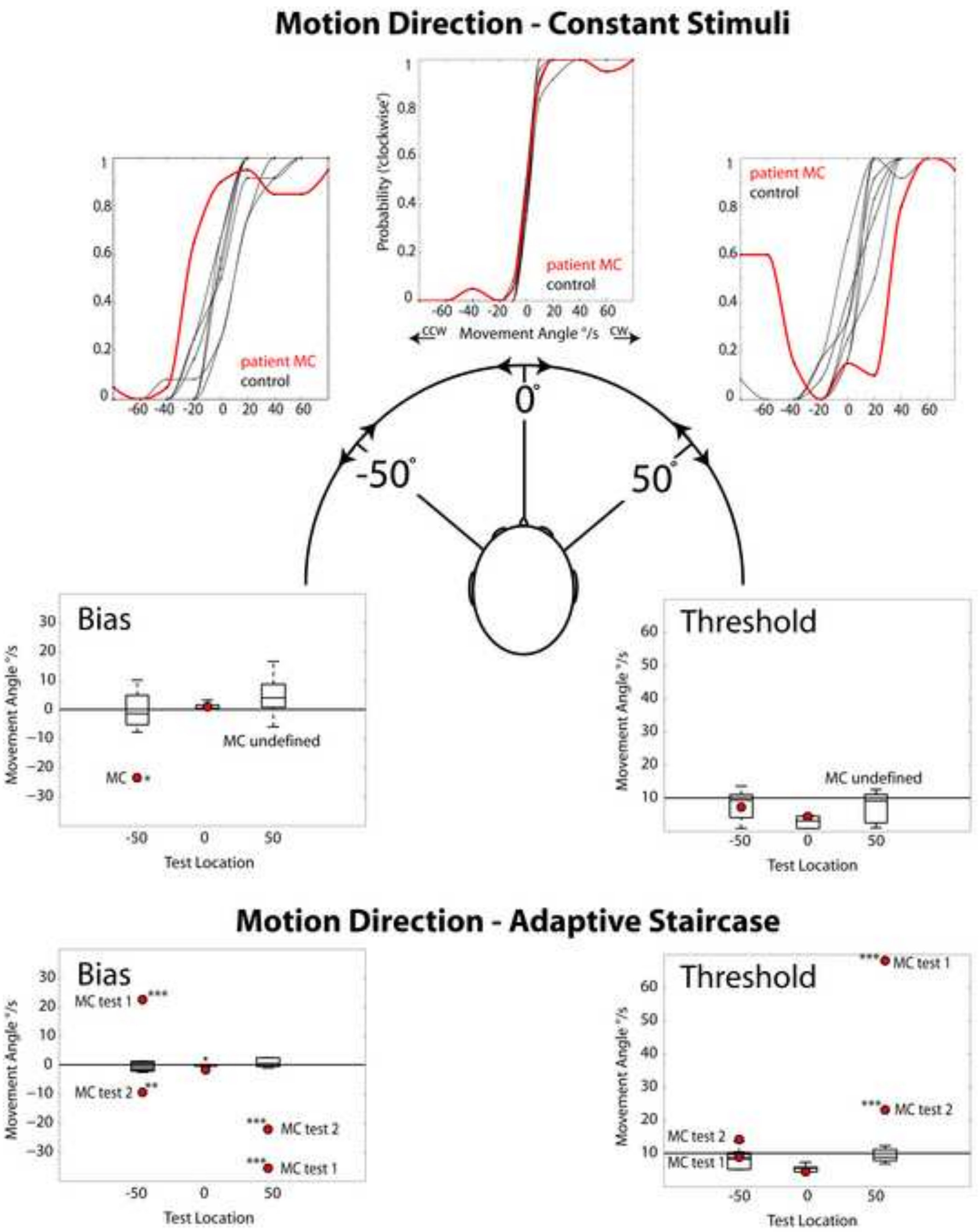
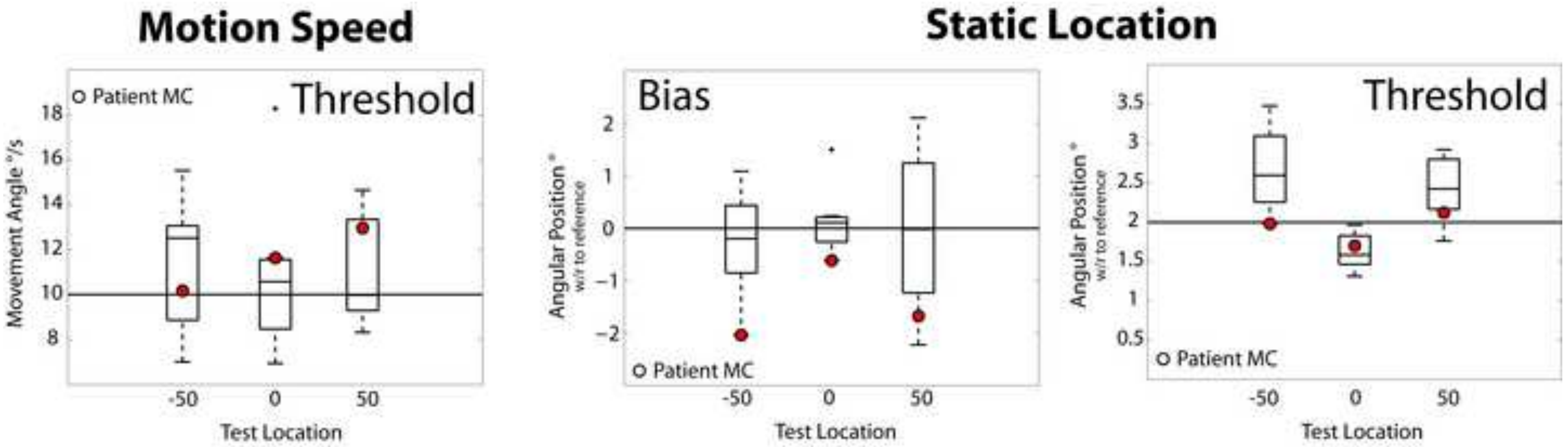


Figure 7


Motion Speed
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