Interhemispheric control of sensory cue integration and self-motion perception

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Abstract—Spatial orientation necessitates the integration of visual and vestibular sensory cues, in-turn facilitating self-motion perception. However, the neural mechanisms underpinning sensory integration remain unknown. Recently we have illustrated that spatial orientation and vestibular thresholds are influenced by interhemispheric asymmetries associated with the posterior parietal cortices (PPC) that predominantly house the vestibulo-cortical network. Given that sensory integration is a prerequisite to both spatial orientation and motion perception, we hypothesized that sensory integration is similarly subject to interhemispheric influences. Accordingly, we explored the relationship between vestibulo-cortical dominance – assessed using a biomarker, the degree of vestibular-nystagmus suppression following transcranial direct current stimulation over the PPC – with visual dependence measures obtained during performance of a sensory integration task (the rod-and-disk task). We observed that vestibulo-cortical dominance had reduced visual dependence. We proceeded to assess the significance of such dominance on behavior by correlating measures of visual dependence with self-motion perception in healthy subjects. We observed that right-handed individuals experienced illusionary self-motion (vection) quicker than left-handers and that the degree of vestibulo-cortical dominance was correlated with the time taken to experience vection, only during conditions that induced interhemispheric conflict. To conclude, we demonstrate that interhemispheric asymmetries associated with vestibulo-cortical processing in the PPC functionally and mechanistically link sensory integration and self-motion perception, facilitating spatial orientation. Our findings highlight the importance of dynamic interhemispheric competition upon control of vestibular behavior in humans. © 2019 The Authors. Published by Elsevier Ltd on behalf of IBRO. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Key words: vestibular cortex, visual dependence, spatial orientation, sensory integration, self-motion perception, vestibular–ocular reflex.

INTRODUCTION

Consider the following scenario: you are sat on a stationary train viewing the train on the adjacent platform which sets off. You may erroneously perceive that you are moving. This illusionary sense of motion (i.e. vection) is suggested to arise due to sensory ambiguity, attributable to conflicting visual and vestibular motion signals. In this case, the question that vestibulo-cortical areas, predominantly represented in the posterior parietal cortex (PPC) (Dieterich et al., 2003; Lopez et al., 2012; Arshad, 2017), are required to resolve is whether: “I am moving?” or, “is the world moving?” Failure to resolve this sensory ambiguity can lead to disorientation, thereby demonstrating that sensory cue integration is a pre-requisite for both motion perception and maintaining spatial orientation (Guerraz et al., 2001; Kamali et al., 2013; Ward et al., 2017).

To orientate ourselves in a busy dynamic environment, the brain must construct and continually update an accurate representation of our world, achieved via multisensory cue integration. In humans, one method of probing sensory integration is to measure an individual's ability to align a target to the perceived gravitational vertical (“earth upright”), both in the presence and absence of background visual motion (“rod and disk task”) (Witkin et al., 1975; Witkin and Goodenough, 1977). If verticality perception is strongly modulated by background motion, then that individual preferentially

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favors visual over vestibular/propioreceptive cues during sensory integration (Guerraz et al., 2001), and is said to be visually dependent.

Previous human psychophysical data suggest that humans weigh sensory cues in proportion to the reliability of each signal (i.e. realistic probability), based on previous experiences (i.e. prior beliefs; Bayesian computation) (Knill and Richards, 1996; Gu et al., 2007; Butler et al., 2010; de Winkel et al., 2010; Fetsch et al., 2010; De Winkel et al., 2013; Fetsch et al., 2013; Alberts et al., 2016). Surprisingly, given the ecological importance of spatial orientation for survival, to-date a neuroscientific mechanism is currently lacking as to why some individuals rely more heavily upon visual cues (Witkin et al., 1975; Witkin and Goodenough, 1977), and others on vestibular (i.e. gravito-inertial cues) or somato-propioreceptive cues (Bronstein et al., 2013). In part such preferences for visual cues during sensory integration have been attributable to an individual's psychological trait (Witkin et al., 1975; Witkin and Goodenough, 1977), a notion supported by recent findings that demonstrate a close link between psychological factors (i.e. anxiety, body vigilance) and increased visual dependence in patients with acute unilateral vestibular loss (Cousins et al., 2014; Cousins et al., 2017).

Putting aside for a moment these psychological influences upon sensory integration, the neural mechanism responsible for the heterogeneity in weighting preferences has been explored empirically in primates. These data suggest that both the dorsal medial superior temporal area (MSTd) (i.e. visual cortical areas) (Gu et al., 2007) and the visual posterior Sylvian (VPS), anatomically located immediately posterior to the parieto-insular vestibular cortex (PIVC) (Chen et al., 2011), play a pivotal role in the integration of visual and vestibular signals, which are required for determining heading (self-motion) perception (Cullen, 2012). In humans, it has been illustrated that disrupting interhemispheric interactions, either via focal lesions or non-invasive modulation of cortical excitability can distort spatial exploration and orientation as well modulating motion perception (Kaski et al., 2016; Bednarzczuk et al., 2017). Given that sensory integration is a prerequisite to both spatial orientation and motion perception, we hypothesized that sensory integration is similarly subject to interhemispheric influences.

Accordingly, here we explored the relationship between vestibulo-cortical dominance – which is subject to interhemispheric control (Arshad, 2017) – assessed using a biomarker, the degree of vestibular-nystagmus suppression following transcranial direct current stimulation over the PPC (Arshad et al., 2015b) – with visual dependence measures obtained during the rod and disk task. Further, we ascertained the functional significance of vestibulo-cortical dominance upon self-motion perception.

**EXPERIMENTAL PROCEDURES**

**Overview**

In experiment 1A we attempted to elucidate the neural mechanism that underpins cue weighting preferences during sensory integration. To achieve this, we implemented the rod and disk task to assess whether cue weighting preference was related to vestibulo-cortical dominance. Accordingly, we utilized the vestibular-nystagmus suppression index to determine vestibulo-cortical dominance (Arshad et al., 2015a,b) and correlated this measure with visual dependence during the rod and disk task (see below for details) (Experiment 1A). Further, in supplemental experiments, we proceeded to examine for any handedness related or motion-directional differences in visual dependence (Experiment 1B). In supplemental experiment 1C, we modulated cortical excitability over the PPC to assess for any potential modulatory effect upon visual dependence measures. In experiment 2, we assessed the functional significance of hemispheric asymmetries associated with the PPC upon self-motion perception. To assess motion perception, participants were seated on a motorized rotating chair surrounded by a curtain marked with vertical black and white stripes which was rotated around the subject (earth-vertical axis) at a constant velocity (see below for details). Participants were alerted to the fact they may feel themselves rotate after a few seconds of viewing the curtain motion and were required to press a button when they experienced this perceptual transition (Arshad et al., 2016a).

**Subjects**

For experiment 1A we recruited 20 right handed subjects (handedness score over 40 (Oldfield, 1971); 10 f, age range 19–24 years, mean age 22 years). For experiment 1B, we recruited a separate set of 10 right and 10 left handed subjects (handedness score over +40 for right handers and under −40 for left handers (Oldfield, 1971)); 10 f, age range 20–26 years; mean age 23.2 years). For experiment 1C, we recruited a new group of 40 right-handed subjects (20 m, age range 20–33 years, mean age 21.2 years), with 20 subjects receiving left anodal stimulation and the fellow 20 subjects receiving left cathodal stimulation (see below for details). Finally, for experiment 2 we recruited the same participants as used in experiment 1B. No subject had any history or active otological, ophthalmological, psychiatric or neurological disorders. This was done by implementing a screening session before participants were recruited into the study and asking them directly if they were currently or ever had been in the past, under the care of a specialist doctor for any eye, ear, brain or psychiatric condition. All subjects provided written informed consent as approved by the local ethics research committee. The authors declare that all experiments on human subjects were conducted in accordance with the Declaration of Helsinki.

**Experimental techniques**

“Rod and Disk” task: Participants initially completed six baseline trials in which they had to set an illuminated line to the perceived gravitational vertical (i.e. subjective visual vertical) in the absence of any visual reference cues. Subsequently, 12 further trials were performed; six during clockwise (CW; 30°/s) and six during counter-clockwise (CCW; 30°/s) full-field background visual roll-motion (randomized order). The line was always calibrated to match true “earth vertical” using a spirit level. Before each trial, the line was...
tilted ±30–50° (“off-set”) by the experimenter in a counterbalanced order, while the participant had their eyes closed. A vertical frontal (roll) plane optokinetic rotating black disk (diameter of 0.9 m) covered with randomly placed luminous dots, was positioned 80 cm directly in front of the participant, with the center of disk (height) in line with the subject’s primary gaze (subtended viewing angle 30°, f.o.v. 60°). Participants stood on steady ground, and the head was secured with an earth-fixed chin rest. In the center of the disk, a secondary black disk was attached with a 0.1-m luminous rod (7° visual angle) that the subjects viewed (N. B. subjects were instructed to continuously stare at the center of the line as to avoid any gaze shifts) so that they could adjust the tilt of the line, via a potentiometer, to what they perceived to be earth-vertical. Deviation values were expressed in degrees (°) reflecting the deviation from true earth vertical (= 0°). Deviations to the right were positive values, whereas deviations to the left were negative values. Visual dependence was calculated as the mean of the absolute (unsigned) values of the rod tilt deviation over the six CW and CCW trials respectively, minus the average deviation across static trials (Roberts et al., 2016).

tDCS (trans-cranial direct current stimulation)

Stimulation was applied using a battery-driven stimulator (neuroConn GMBH, ilmenau, Germany), using a previously described montage, namely either unipolar cathodal (test condition) or anodal (active control condition—see next section for details) stimulation over the left posterior parietal cortex (P3: international 10–20 system for EEG electrode placement; electrode placement area 25 cm²). The reference (i.e. anodal) electrode was placed at an extracephalic site (i.e. over the ipsilateral shoulder) (Been et al., 2007; Utz et al., 2010). The current had a ramp-up time of 10 s, at which point a constant current (1.5 mA) was applied for 15 min. The current ramped down in a 10-s fade-out period (Arshad et al., 2014, 2015a,b; Nigmatullina et al., 2016).

Establishing vestibulo-cortical dominance

We have previously demonstrated that the degree of vestibular nystagmus suppression induced following cortical inhibition of the left posterior parietal cortex reflects the degree of vestibulo-cortical hemispheric dominance (Arshad et al., 2015a,b). To determine this, participants initially underwent caloric stimulation of both the right and left ear separately with cold water which was used as a baseline measure of vestibular nystagmus. They then received either cathodal (test) or anodal (active control) transcranial direct current stimulation (tDCS) over the left posterior parietal cortex, randomized across participants. Following tDCS, the caloric irrigations were repeated to assess the mean % change in slow phase velocity of the vestibular nystagmus induced by the tDCS. This was quantified by calculating the nystagmus suppression index: subtracting the peak post-tDCS SPV from the peak pre-tDCS SPV divided by the peak pre-tDCS SPV × 100. Note, we only expected to observe nystagmus suppression following cathodal but not anodal stimulation, with the latter specifically implemented as an active control for any non-specific effects associated with electrical stimulation (Arshad et al., 2014, 2015a,b; Nigmatullina et al., 2016).

We only stimulated with tDCS the PPC over the left but not the right hemisphere, as previous research has illustrated that right hemisphere stimulation exerts no modulation of vestibular responses in right-handed individuals. This lack of any modulatory effect following inhibition of the PPC in the right hemisphere is somewhat surprising, since such inhibition disrupts interhemispheric interactions and theoretically should affect vestibular processing (Arshad et al., 2014). We propose that the lack of modulation is attributable to the fact that in right handers, the right hemisphere can better compensate than the left for the induced inhibition via cortical stimulation, thanks to its superior preponderance for vestibular processing (Arshad et al., 2014). An alternative, but not a mutually exclusive explanation, is that there is an on-going functional asymmetry between the two parietal cortices; hence, the right hemisphere exerts stronger inhibition over the left hemisphere, a notion supported by the previous findings demonstrating that parietal interhemispheric connections are asymmetric (Koch et al., 2011). Accordingly, throughout the manuscript we adopt the terminology interhemispheric influences as via the application of tDCS we are specifically modulating interhemispheric interactions and subsequently observing the effect upon vestibular processes.

Vestibular stimulation and eye movement recording

Following otoscopy to exclude local contra-indications, participants underwent caloric stimulation (of both the right and left ear—each separated by 5 min to avoid carry over effects) while laying supine on a couch with their head tilted up by 30° (ensuring maximal horizontal semi-circular canal activation) to elicit the vestibular–ocular reflex (VOR). Irrigations were performed with cold water (30 °C) with a flow rate of 500 ml/min for 40 s (CHARTR VNG; ICS medical) which elicits vestibular nystagmus with a fast phase beating in the opposite direction to the irrigated ear. Eye movements were recorded using a head-mounted infra-red binocular video-oculography (VOG) system (CHARTR VNG; ICS medical), calibrated using a 0.25-Hz pursuit target. Eye movements were analyzed using an automated computerized program (CHARTR VNG; ICS medical) that removes the fast phases of the nystagmus, thus enabling the plotting of each individual slow phase velocity (SPV) over time. Response intensity was determined by identifying the peak SPV.

Opto-kinetic stimulation (OKS) to induce illusory self-motion (vection)

For experiment 2, participants were seated on a motorized rotating chair surrounded by a visual stimulus that consisted of a 1.44-m diameter drum marked with vertical black and white stripes. Subjects viewed the drum at a fixed distance of 0.72 m (Fig. 4A). To generate the OKS, the drum was...
rotated around the subject in an Earth-vertical axis at a constant velocity of 40°/s, either right or leftwards (randomized order). Viewing full-field OKS, as we implemented, can induce two different possible perceptual states of motion, namely either, (i) "visual world" or, (ii) "self", motion. The initial percept that is experienced by the individual is that of visual world motion and typically after approximately 15–20 s of viewing full-field OKS the subjective experience transitions to that of self-motion. Subjects were required to inform the experimenter (via a button press) when they experienced the perceptual state of self-motion (Arshad et al., 2016a). All subjects were naive to vection and received three practice trials before the experiment.

Experimental Protocol

We have summarized the implemented protocol for the different experiments in Table 1. For experiment 1A, participants initially underwent both right and left ear cold caloric irrigation. They also had their visual dependence assessed using the "rod and disk" task. These two tasks were carried out in a randomized order. Participants then received 15 min of tDCS over the left posterior parietal cortex. Following application of tDCS, participants received another right and left ear cold caloric irrigation to calculate the post-tDCS peak slow phase velocity. For experiment 1B and 2, participants performed the "rod and disk" task to assess their visual dependence. We also assessed the time taken to develop vection during full-field OKS. These two tasks were carried out in a randomized order. In experiment 3, participants firstly performed either the Rod and Disk task to obtain baseline values of visual dependence or caloric irrigations to obtain baseline measures of slow phase eye velocity (vestibular nystagmus suppression index) (randomized order). We then applied tDCS over the left PPC as detailed in the methods, with 20 participants receiving cathodal stimulation while the remaining 20 participants received anodal stimulation. After brain stimulation, we calculated each individual's nystagmus suppression index (repeat caloric) and repeated the Rod and Disk task (randomized order). From this repeat measure of visual dependence, we calculated the % change in visual dependency pre/post tDCS and related it to an individual's nystagmus suppression index.

Statistical analysis

All statistical analysis was conducted in SPSS Statistics 23 (IBM Corp.). Normality was tested using the Shapiro–Wilk test. For all data sets the p value was >0.05 thereby indicating that the data were normally distributed. Equal variances were assessed using Levene’s test and indicated equal variances. Correlations were assessed using Pearson’s correlation coefficients and differences between groups were assessed for by using Bonferroni corrected t-tests (corrected significance level was set to P < 0.05).

RESULTS

Experiment 1

As illustrated in Fig. 1, we observed a significant negative correlation (R² 0.65, p < 0.001) between the vestibular nystagmus suppression index and the degree of visual dependence. That

Table 1. Summary of the implemented experimental protocol.

| Experiment 1A | Experiment 1B and 2 | Experiment 1C |
|---------------|---------------------|---------------|
| Right handed participants underwent a right and left cold caloric irrigation. Visual dependence assessed using the "rod and disk" task. Two tasks were carried out in a randomized order. | Right and left handed Participants undertook the "rod and disk" task to assess their visual dependence. Implemented the OKS task to assess vection. Two tasks were carried out in a randomized order. | Right handed participants underwent a right and left cold caloric irrigations. Visual dependence assessed using the "rod and disk" task. Two tasks were carried out in a randomized order. |
| Participants then received 15 min of left cathodal tDCS over the left posterior parietal cortex. Following tDCS participants had another right and left cold caloric irrigation. | | Participants then received 15 min of tDCS over the left posterior parietal cortex. Following tDCS participants had another right and left cold caloric irrigation. Visual dependence reassessed. Tasks performed in a randomized order. |
is, following left hemisphere cathodal stimulation, those individuals that exhibited greater vestibular nystagmus suppression were less visually dependent compared to individuals with a lower nystagmus suppression index.

For supplemental experiments 1B and C (Fig. 2), we assessed for any modulation of visual dependency measures that were associated with either (i) handedness (Dieterich et al., 2003; Arshad et al., 2013; Arshad, 2014; Arshad et al., 2015a,b), (ii) background roll-motion direction (Watanabe, 2001; Teramoto et al., 2004; Figliozzi et al., 2010; Arshad et al., 2016a) or, (iii) changes in cortical excitability of the PPC.

No overall group difference in visual reliance was observed when comparing right and left handed individuals ($t(18) = -1.16, p = 0.26$; t-test Bonferroni corrected), but we did observe that visual dependence was modulated by the background motion direction in right (Fig. 2B) but not left handed individuals (Fig. 2B). That is, in right handers, visual dependency exhibited during the “rod and disk” task was lower during CCW compared to CW motion ($t (9) = 2.37, p < 0.05$; paired t-test; Bonferroni corrected; Fig. 2B). In left handers, no difference in visual dependency was observed when comparing CW versus CCW motion ($t (9) = -0.64, p > 0.05$ paired t-test; Bonferroni corrected).

Further analysis revealed significant differences in visual dependence for motion direction that stimulated the same hemisphere in right and left handers. That is, significantly less visual dependence was observed in right handers during (CCW) compared to (CW) motion in left handers ($t (18) = 1.93, p < 0.05$; t-test; Bonferroni corrected). No differences were observed when comparing (CW) motion in right handers versus (CCW) motion in left handers ($t (18) = -0.36, p > 0.05$ t-test; Bonferroni corrected).

As illustrated in Fig. 3 (N.B. showing right-handed subjects only), following left hemisphere cathodal stimulation...
to modulate PPC excitability (experiment 1C), we observed a negative correlation between vestibulo-cortical dominance (i.e. nystagmus suppression index) and the percentage change (pre/post-tDCS) in visual reliance during CW roll motion ($R^2 = 0.66; p < 0.01$; Fig. 3A), but a positive correlation during CCW roll motion ($R^2 = 0.63; p < 0.01$; Fig. 3B). No relationship was observed following anodal stimulation for either CW ($R^2 = 0.0004; p > 0.05$) or CCW motion ($R^2 = 0.07; p > 0.05$).

The above reported findings suggest that the degree of visual dependence appears to be related to vestibulo-cortical hemispheric dominance. However, one remaining question is the functional relevance of this cortical mechanism. That is, what effect, if any, vestibulo-cortical hemispheric dominance has upon motion perception. This is addressed below in Experiment 2.

Experiment 2

This experiment revealed a significant correlation between an individual’s degree of visual dependence and the timing of the perpetual transition (from world to self-motion), during right but not leftward curtain motion (Fig. 5). Critically, the correlation observed was reversed depending upon the individual’s handedness. That is, in right handers, for rightward curtain motion participants with lower visual dependence took longer to perceive self-motion ($R^2 = 0.35; p < 0.01$ Fig. 5A), whereas in left-handers lower visual dependence was associated with a shorter perceptual transition time ($R^2 = 0.45; p < 0.01$ Fig. 5C). No relationship was observed between visual dependence and the timing of the perceptual transition during leftward motion in neither right ($R^2 = 0.005; p > 0.05$ Fig. 5B) or left ($R^2 = 0.004; p > 0.05$ Fig. 5D) handed individuals. Moreover, we observed that the mean perceptual transition time was significantly quicker in right (16.4 s) compared to left (25.6 s) handed individuals ($t (18) = -7.03, p < 0.001$; t-test; Fig. 4C).

DISCUSSION

Our principal aim in this study was to investigate how interhemispheric asymmetries associated with vestibulo-cortical areas in the PPC underpin weighting preferences during sensory cue integration and to probe its functional significance upon self-motion perception. Previous data have demonstrated that disruption of interhemispheric interactions between the PPC areas can distort spatial orientation and modulate vestibular thresholds (Kaski et al., 2016; Bednarczuk et al., 2017). Accordingly, we postulated that sensory integration may similarly be subject to interhemispheric interactions associated with the emergent dominance in vestibulo-cortical processing in the PPC (Arshad, 2017).

In line with the above prediction, we observed a relationship between visual dependence and the degree of vestibulo-cortical dominance as reflected by the vestibular nystagmus suppression index following cathodal stimulation of left PPC (Arshad et al., 2015a,b). It is important to recall that in right-handed individuals, there exists right hemisphere dominance for vestibular cortical processing (Dieterich et al., 2003; Arshad et al., 2013). Herewith, we observed that less right hemisphere dominant individuals, as reflected by a lower nystagmus suppression index following left cathodal tDCS, had increased visual dependency measures. Thus, greater right hemisphere vestibulo-cortical dominance was associated with increased reliance on gravito-inertial cues during performance of the rod and disk task.

Given that left cathodal tDCS involves spreading electrical current which suppresses the VOR (as implemented to calculate the nystagmus suppression index), it follows then
that it could be the case that tDCS is impacting upon either, (i) pursuit and/or VOR suppression mechanisms and, (ii) peripheral vestibular afferents directly. However, these two possibilities can be ruled out, given that we have previously demonstrated that the implemented montage does not modulate pursuit eye movements or VOR suppression (Ahmad et al., 2014), and that tDCS, unlike galvanic stimulation, does not induce torsional nystagmic eye movements (Koch et al., 2011; Szczepanski and Kastner, 2013). Taken together, current evidence suggests that left cathodal stimulation modulates vestibular responses due to suppression of the left parietal cortex. In turn this results in potentiating right hemisphere dominance and renders the left hemisphere less able to process the vestibular nystagmus. Thus, greater vestibular nystagmus suppression following left PPC cathodal tDCS, implies increased right hemispheric vestibulo-cortical dominance (Arshad et al., 2014, 2015a,b).

Further support for the role of reduced right vestibulo-cortical dominance in individuals with increased visual dependence is provided by the results of supplemental experiments 1B and 1C. Specifically, there is previous evidence that leftward roll motion tilt (from studies that have applied left-ear anodal galvanic stimulation) preferentially activates the right hemisphere in right handers (Fink et al., 2003). Of note, CCW visual motion induces a perceived body tilt to the right and a (compensatory) postural response to the left as observed during left-ear anodal galvanic stimulation. Our findings illustrate that visual dependence values during CCW background roll motion were smaller than for CW motion, in right but not left-handers (Fig. 2B). No overall handedness-related differences were observed upon visual dependence when comparing right vs left handers, although reduced visual dependence was consistently observed in right compared to left handers when the motion stimulus preferentially activated the right hemisphere (i.e. CCW motion in right handers vs CW motion in left handers). No differences between right and left handers occurred when the task preferentially activated the left hemisphere (i.e. CW motion in right handers vs CCW motion in left handers). These findings are in line with the correlation observed in experiment 1A (Fig. 1) and illustrate that more visually dependent individuals, who are driven by visual as opposed to gravito-inertial cues, have a less strong vestibulo-cortical representation.

Our results from experiment 1C further support the above view that reduced right hemispheric vestibulo-cortical dominance is associated with increased visual dependence. That is, during CW visual motion (i.e. preferential left hemisphere stimulation in right handers), inhibition of the left parietal cortex (cathodal stimulation) resulted in individuals with greater right hemisphere dominance (larger nystagmus suppression index) exhibiting comparatively less increase in visual dependence following tDCS. This is attributable to a tDCS-mediated inhibition of the left hemisphere and thus shifting the processing to the right hemisphere. Accordingly, those individuals with greater right hemisphere dominance exhibit less change in visual dependence, in accord with the correlation illustrated in Fig. 1. Conversely, inhibition of the left parietal cortex during CCW motion (i.e. preferential right hemisphere activation) resulted in reduced visual dependence in individuals with less right hemisphere dominance. This is due to concurrent inhibition of the left hemisphere with tDCS and excitation of the right hemisphere due to the visual stimuli, with the net result of increased reciprocal inhibition over the right hemisphere (Koch et al., 2011; Szczepanski and Kastner, 2013). Thus, greater reduction in visual dependency is observed in those less right hemisphere dominant individuals (i.e. lower nystagmus suppression index) as in these individuals the left hemisphere is more readily able to exert inhibition over the right hemisphere.

To surmise, the findings from experiment 1 support the notion that individuals with greater right vestibulo-cortical hemispheric dominance express comparatively less visual dependence. More broadly, our data are in line with the notion that the lateralization of the vestibular cortex is more pronounced in left handers and thus less susceptible to interhemispheric influences (Nigmatullina et al., 2016). Further, our findings are also consistent with previous reports that demonstrate the critical role of the right parietal cortex for verticality perception (Dieterich and Brandt, 1993; Brandt et al., 1994; Perennou et al., 2008; Kheradmand et al., 2015) and that visual cortex excitability is not related to an individual’s visual dependence (Lubeck et al., 2016). In experiment 2, we proceeded to ascertain the functional significance of vestibulo-cortical hemispheric dominance as reflected by measures of visual dependence upon self-motion perception. We observed that the timing of an individual’s perceptual transition from world to self-motion during optokineti c stimulation (OKS) (circular-vection latency) could be predicted by the degree of an individual’s visual dependence. We observed that in right handers lower visual dependence was associated with a longer perceptual transition time. Conversely in left handers lower visual dependence was associated with a shorter perceptual transition time. Critically though, this relationship in both right and left handers was found to only hold during right but not leftward motion (Arshad, 2017).

This motion direction asymmetry (i.e. relationship for right but not leftward motion) can be attributed to the notion that rightward motion induces interhemispheric conflict. That is, in right-handers, during rightward OKS, the perception of vection implicates the right hemisphere (vestibular cortex) in order to consciously perceive self-motion (Brandt et al., 1998; Bense et al., 2006) in addition to the left hemisphere being concurrently implicated as the perceived rightward visual motion shifts covert attention rightwards (Moore et al., 2003; Figliozzi et al., 2005), thereby inducing interhemispheric conflict (Arshad, 2017). In left handers, the vestibular cortex is lateralized to the left hemisphere (Dieterich et al., 2003; Arshad et al., 2013) and one would naturally assume that in left handers the rightward OKS would similarly shift covert attention rightwards (Moore et al., 2003; Figliozzi et al., 2005). However, this would not induce interhemispheric conflict and yet we observed a relationship between visual dependency measures and time taken to develop vection during rightward OKS in left handers (Fig. 5). Such a finding could fit with an interhemispheric conflict account if the attentional shift due to rightward
visual motion was reversed in left-handed individuals (i.e., covert attentional shift to the left during rightward visual motion). Such an intriguing possibility is supported by recent findings which have probed auditory localization in right and left-handed individuals, essentially implying an opposing perceptual response dependent upon handedness to sensory stimulus (Bareham et al., 2015). Thus, based on this assumption of opposing shifts in covert attention in left-handed individuals (Bareham et al., 2015), the rightward OKS induces a covert attentional shift to the left mediated by the right hemisphere while the vestibular cortex is lateralized to the left hemisphere (Dieterich et al., 2003; Arshad et al., 2013), thereby inducing interhemispheric conflict (Arshad, 2017). During leftward motion, in both right and left-handed individuals, the same hemisphere houses the vestibular cortex and mediates the shift of covert attention, thus not inducing interhemispheric conflict (Arshad, 2017).

Fundamentally, the brain is required to resolve the induced interhemispheric conflict via unihemispheric inhibition (Arshad, 2017). Previous work has demonstrated that vision requires inhibition of vestibular cortical areas (Brandt et al., 1998), predominantly represented in the right hemisphere in right-handed individuals, and by the left hemisphere in left-handed individuals (Dieterich et al., 2003; Lopez et al., 2012; Zu Eulenburg et al., 2012; Arshad et al., 2013). Therefore, in order to resolve interhemispheric conflict and induce vision, in right-handed individuals, the left hemisphere is required to inhibit the right (Kinsbourne, 1977; Szczepanski et al., 2010; Szczepanski and Kastner, 2013; Arshad et al., 2016b). In individuals with greater right vestibulo-cortical hemisphere dominance as reflected by lower visual dependence, the left hemisphere is less able to inhibit the right, resulting in a longer perceptual transition time for more visually-dependent right-handed individuals. In left-handed individuals, the right hemisphere is required to inhibit the left hemisphere which predominantly houses the vestibular cortex to induce vision (Brandt et al., 1998; Dieterich et al., 2003; Arshad et al., 2013). Hence, left-handed individuals who are less visually dependent (i.e., more right hemisphere dominant) are more readily able to inhibit the left hemisphere and thus perceive vision sooner than more visually dependent left-handed individuals.

Further, it should be noted that we found that the perceptual transition time to be significantly longer in left compared to right-handed individuals, thereby further demonstrating handedness-related differences upon self-motion perception, and supporting the notion that the vestibular cortex is more strictly lateralized in left-handers (Nigmatullina et al., 2016).

To conclude, it is the case that to-date vestibular research has lagged behind other sensory systems (Parker and Newsome, 1998; Luna et al., 2005) with respect to exploring how neural signals and their associated uncertainty inform perceptual decision-making. Much of the research that is currently available which addresses how sensory cues are integrated to inform heading perception has been conducted in primates (Gu et al., 2007; Morgan et al., 2008; Angelaki et al., 2009; Fetsch et al., 2010; Chen et al., 2011; Cullen, 2012; Fetsch et al., 2013; Smith et al., 2017). In this study, we illustrate that in humans, interhemispheric asymmetries between the posterior parietal cortices—which form part of the vestibular cortical network—predict cue weighting preferences during sensory integration. That is, greater right hemisphere vestibulo-cortical dominance is associated with increased reliance upon gravito-inertial as opposed to visual cues during sensory integration. Functionally, such interhemispheric asymmetries were found to impact upon motion perception, which in addition to sensory integration is a pre-requisite for maintaining spatial orientation.

Finally, in addition to the general scientific meaning of our findings there could potentially be wider clinical implications, given that over-reliance on visual rather than gravito-inertial cues during sensory integration is associated with poorer clinical-outcome following acute vestibular dysfunction (Cousins et al., 2014, 2017). Thus, future clinical studies should directly examine the role of hemispheric influences.
on outcome measures and its relationship with motion perception in patients with vestibular dysfunction.

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