Recruitment of Periventricular Parietal Regions in Processing Cluttered Point-Light Biological Motion

Recent findings point to the existence of a cortical–subcortical parietal network that drives attention-related integration of features and elements. Here we ask whether the functioning of this network might be modulated by early periventricular lesions. To this end, a cohort of adolescents who were born premature with different severity of bilateral periventricular leukomalacia (PVL) and two groups of matched peers (term-born adolescents and former preterms with normal MRI scan) were shown a set of impoverished point-light stimuli. Observers had to detect a point-light walker embedded in an array of distracters mimicking the motion of the target’s dots. Patients exhibited higher susceptibility to distortions caused by distracters. In patients only, sensitivity to the point-light figure highly correlates not just with performance on additionally administered feature integration tasks but also on visual attention-demanding IQ tasks. Moreover, the sensitivity index, as well as the values of both IQ factors, decreases with an increase in the volumetric PVL extent in the parieto-occipital region. No relationship was found between these variables and the lesion extent in the frontal or temporal periventricular regions. The data suggest that visual integration and attention in processing cluttered point-light displays are intimately connected. Most importantly, periventricular parieto-occipital regions might be part of a distributed network recruited in deployment of the posterior attentional system. The functioning of this system seems to be vulnerable to bilateral periventricular damage even if it occurs very early in brain development.

Keywords: attention-related visual integration, distracters, medical psychophysics, periventricular lesions, point-light biological motion, posterior cortical–subcortical parietal network

Introduction

Recent data point to the existence of a special cortical–subcortical parietal network subserving integration of local features and elements that requires attentional resources (e.g. Reynolds and Desimone, 1999; Robertson, 2003). Functional magnetic resonance imaging (fMRI) indicates that the right intraparietal sulcus (IPS) shows increased activation when a neutral target appears among salient distracters (Marois et al., 2000). Positron emission tomography (PET) reveals that the superior parietal cortex is activated when perceivers search for a conjunction target in a cluttered display, but not for a single feature (Corbetta et al., 1995). Lesion studies show that patients with bilateral damage to parietal cortex are impaired in filtering distracters and the magnitude of the impairment increases with distracter salience (Friedman-Hill et al., 2003). Moreover, the attentional network of the parietal cortex is involved in visual binding only when spatial relationships between object features or elements are ambiguous (Shafritz et al., 2002). Subcortical structures, such as pulvinar, cerebellum, and lateral geniculate nucleus (LGN), along with parietal cortex, seem to be part of this recently recognized network (O’Connor et al., 2002). Damage to the pulvinar of the thalamus that contains many interconnecting fibres projecting to the parietal lobe may result in breakdown of feature binding and in spatial attention imbalance (Ward et al., 2002). Due to the close linkage with the parietal cortex, periventricular parieto-occipital regions appear to be a putative candidate for subcortical recruitment in the functioning of this system. For clarification of this issue, we used point-light biological motion methodology to investigate patients who were born premature and suffer congenital bilateral damage to periventricular parieto-occipital regions.

It is well known that the visual system is exquisitely sensitive to biological motion represented solely by a set of moving dots attached to the main joints of the invisible human body (Johansson, 1976). In both healthy perceivers and patients, point-light stimuli have proven to be a valuable tool for exploration of the capacity to integrate the local elements in different locations into a cohesive percept (Cowey and Vaina, 2000; Tadin et al., 2002; Vaina et al., 2002; Blake et al., 2003; Fine et al., 2003; Pavlova and Sokolov, 2003). Two outcomes of the studies on point-light biological motion are of primary relevance for the present work. First, following the initial findings by Cutting et al. (1988), it has been established that the mature visual system robustly tolerates embedding of a point-light walker into an array of moving distracters mimicking the motion of point-light dots (e.g. Bertenthal and Pinto, 1994; Neri et al., 1998; Pavlova and Sokolov, 2000). Secondly, although perception of point-light stimuli is traditionally thought to be a kind of ‘pop-out’ phenomenon, which is considered to be the hallmark of pre-attentive processing, recent psychophysical and brain imaging data demonstrate that the integration of the dots into the overall kinetic form of a point-light figure requires attentional resources (Cavanagh et al., 2001; Thornton et al., 2002; Battelli et al., 2003), and the pattern of brain activity in response to a point-light walker might be affected by the withdrawal of attention (Pavlova et al., 2000; Vaina et al., 2001).

Here we ask whether visual detection of a point-light walker embedded in a number of similarly moving distracters is impaired in patients with early bilateral damage to periventricular regions. Periventricular leukomalacia (PVL), the dominant form of brain injury in individuals who are born premature, affects the parieto-occipital white matter, and extends to the regions around the bodies of the lateral ventricles. This lesion pattern is of early origin (third trimester of pregnancy) and high...
structural homogeneity (Krägeloh-Mann et al., 1999), and, therefore, may be considered a proper model for addressing the issue of how topography and extent of subcortical brain damage of similar timing relate to functional abnormalities (Pavlova et al., 2003; Krägeloh-Mann, 2004). To prove the specificity of engagement of periventricular regions in the attention-related visual integration, tasks on visual and non-visual attention and perceptual organization, as well as a one-back repetition task with unmasked point-light displays were administered to participants.

Materials and Methods

Participants

Three groups of adolescents (30 children, aging range 13–17 years) participated. The first group comprised 14 (six female and eight male) patients born premature at 27–33 weeks of gestation. All of them suffered bilateral periventricular leukomalacia (PVL) of different severity revealed on structural MRI scans [Fig. 1C (third row) for participant TSA with mild PVL and Fig. 1D (fourth row) for participant SSA with severe PVL]. Two male patients did not come for neuropsychological examination, and one female patient with PVL was excluded from the data processing because of cortical lesions revealed on her MRI scan. This left the data sets from 11 patients with PVL for the subsequent data processing. The second group consisted of eight (four male and four female) adolescents born premature who had MRI scans without any identifiable signs of brain lesions or other abnormalities (Fig. 1B, for the representative participant KRO). Participants in the both groups were recruited on a voluntary basis from a data pool of the Department of Paediatric Neurology and Child Development, Children’s Hospital, University of Tübingen. The third group comprised eight (five male and three female) term-born adolescents without a history of neurological, psychiatric or developmental disorders. The MRI data from the representative term-born participant HDI are shown in Figure 1A (first row). Term-born adolescents were recruited as volunteers from the local community. Former preterms without PVL and term-born participants served as controls. All participants had normal or corrected-to-normal vision and attended the mainstream school with the exception for one male patient with PVL who attended a special school for motor disabled children. Verbal IQ >85 was an inclusion criterion for all participants. In 8 of 11 patients with bilateral PVL, a leg-dominated bilateral spastic cerebral palsy (BS-CP) was diagnosed. In earlier work (Pavlova et al., 2003), we have shown that in patients with PVL, the visual sensitivity to biological movement is not related to this type of motor disorder. The participant information is summarized in Table 1. Informed written consent was obtained from the participants and their care-providers in accordance with the requirements of the Ethical Committee of the Faculty of Medicine at the University of Tübingen (Ethik-Kommission der Medizinischen Fakultät der Universität Tübingen).

Structural MRI and Quantification of Lesion Extent

From all participants, structural MRI scans were obtained as axial dual turbo spin-echo slices (35 axial slices, $T_R$ (repetition time) = 4800 ms, $T_E$ (echo time) = 85 ms, 4 mm slice thickness) and as T1-weighted 3-D data sets (MPRAGE, 128 sagittal slices, $T_E = 9.7$ ms, $T_R = 4$ ms, flip angle 8°, $T_I$ (inversion time) = 300 ms, 1.5 mm slice thickness) through a 1.5 T scanner.
One type of stimuli represented a canonical point-light walker (target) embedded in an array of 44 distracters competing with motions of the target’s dots (Fig. 2A). The other type of stimuli was a 55-dot mask: additional 11 dots were added to the target-absent displays so that their density matched that of the target-present displays. A canonical point-light figure comprised 11 dots placed on the joints (ankles, shoulder, etc.) of an invisible human body (Fig. 2B). It was seen moving and facing right, in a sagittal view, with no net translation. A gait cycle was accomplished in 40 frames with frame duration of 36 ms. The target subtended a visual angle of 4° in height and 2.8° in width at the most extended point of a gait cycle. A forty-four-dot distracter consisted of four sets of spatially scrambled dots on the joints of a canonical walker. Within a set, the motion of each dot mimicked the motion of one of the dots defining the point-light target figure. The size, luminance and phase relations of the dots also remained unchanged. In a display, moving dots were distributed within a region of about 5° in height by 7° in width.

Participants were tested individually. An observer sat at a distance of 57 cm from the screen. His or her head was fixed in a head-and-chin rest. Each of three experimental runs (32 stimuli in a run × 3 runs = total 96 stimuli) was preceded by a 10-s exposure to the target. Each run contained an equal number of stimuli with and without the target; the order of stimulus presentations was randomized. The stimulus duration was 1 s. In a confidence rating procedure, by using a five-point equal-spaced scale (1, confident of the presence of a target from 100 to 80%; 2, from 80 to 60%; 3, from 60 to 40%; 4, from 40 to 20%; and 5, from 20 to 0%), participants had to detect the presence of a canonical point-light figure. No feedback was given regarding performance.

One-back Repetition Task
For this task, a non-camouflaged canonical point-light walker and a scrambled point-light configuration were used (Fig. 2B). For generation of a scrambled display, the spatial positions of dots were randomly rearranged on the screen so that the display lacked an implicit coherent structure of a canonical figure. The motion of each point of the scrambled display was identical to the motion of one of the points defining the canonical figure. The size, luminance, and phase relations of the dots also remained unchanged. The configurations were computer-generated by Cutting’s algorithm (Cutting, 1978), and subtended a visual angle of 9° in height and 6° in width. A randomized set of 200 stimuli with an equal number of both display types (canonical and scrambled configuration) was presented. Each stimulus appeared for 650 ms on a blank screen with an inter-stimulus interval that varied randomly between 2.5–5.0 s. Participants had no explicit identification task. Instead, they performed a one-back repetition task signalling a repeated...
stimulus of each type with a key press. This task obligates attention to both types of stimuli. For analysis of errors, conducted separately for each subject, we calculated the miss rate as a ratio of the number of failures to respond to the second identical stimulus of each type to the total number of the required responses to this type of stimulus. Similarly, for analysis of the false alarm rate, the number of the false alarms for each type of stimulus was divided by the total number of trials in which this type of error might occur.

Results

Detectability of Camouflaged Point-light Figure

Even during the familiarization with the unmasked target, all participants spontaneously reported seeing the point-light walker. Their impression of the walking figure was vivid, and upon request all participants were able to indicate the direction the walker was facing as well as the apparent direction of locomotion. For psychophysical data processing, the jackknife procedure was employed to calculate statistically unbiased parameters of receiver operating characteristic (ROC) curves from pooled rating-method data (Dorfman and Berbaum, 1986). Data analysis was performed on individual values of the jackknife estimation of the area under the ROC curve (Az), a standard measure of sensitivity in signal detection theory (Macmillan and Creelman, 1991). ROC analysis shows that detectability of the target embedded in an array of competing distracters by patients with lesions was substantially lower than it was for the control groups (t-test, one-tailed; P < 0.0002). There were no significant differences in sensitivity between former preterms without lesions and term-born participants (t-test, one-tailed, P = 0.89). This indicates that the lower sensitivity in patients with lesions is not simply due to preterm birth.

Relation of Detectability to IQ Factors

Performance of patients on both perceptual organization and visual attention tasks was significantly lower than in the control groups (t-test, one-tailed; P < 0.01). Again, there were no differences in performance on these tasks between the control groups (t-test, one-tailed, P = 0.41). In patients, the detectability of a point-light target embedded in an array of competing distracters correlates highly with performance on perceptual organization tasks (IQ factor PO; Pearson product–moment correlation, r = 0.711, P < 0.02), and on visual attention tasks (PS; r = 0.686, P < 0.02; Fig. 3A). Notably, no linkage was found between the sensitivity index and the IQ factor FD, which is based on effortful non-visual attentional tasks (r = 0.27, n.s.; Fig. 3B). Patients were also as good as both control groups in performance on FD tasks. In both control groups, neither the PO factor (r = -0.119, r = 0.172, n.s., for preterm and term-born controls, respectively), nor the PS factor (r = -0.481, r = 0.488, n.s., for preterm and term-born controls, respectively) related substantially to the sensitivity index (Fig. 3C, D).

Linkage between Detectability and Parieto-occipital Periventricular Lesions

We hypothesized that periventricular parieto-occipital regions might be engaged in processing of cluttered point-light configurations. Therefore, we addressed the issue of whether the severity of lesions in the parieto-occipital complex is related to the ability to detect a point-light figure embedded in a complex array of similar distracters. We also proved the relationship between the severity of lesions and performance on perceptual organization and visual attention tasks administered to the participants in the course of neuropsychological examination.

The sensitivity index (Az) correlated negatively with the volumetric extent of periventricular lesions over the parieto-occipital complex (Pearson product–moment correlation, r = -0.711, P < 0.02, Fig. 4A; the values here and below are given for both hemispheres together if not stated otherwise), whereas no significant correlation was found between the sensitivity index and the volumetric extent of PVL in the frontal and the temporal region (r = -0.303, r = -0.421, n.s., respectively). In both control groups, no relationship was found between the sensitivity and the volumetric ventricular extent in the parieto-occipital region (r = -0.067, r = 0.184, n.s.; for preterm and term-born controls, respectively).

In patients, not only the value of the PO factor, but also the PS factor based on visual attention tasks decreases with increases in the volumetric PVL extent in the parieto-occipital region (r = -0.716, r = -0.614, P < 0.05, for PO and PS, respectively; Fig. 4B). No significant relationship was found between these values and the severity of PVL in the frontal (r = -0.476, r = -0.385, n.s., for PO and for PS, respectively), and in the temporal region (r = -0.548; r = -0.414, n.s., for PO and PS, respectively). In both
control groups, no relationship was found between the IQ factors PO and PS, and the volumetric parieto-occipital ventricular extent (Fig. 4C,D).

Taken together, the findings indicate the specificity of the relationship between the parieto-occipital periventricular lesions and attention-related integration of elements in cluttered point-light displays. This outcome is also confirmed by the lack of linkage between the severity of periventricular lesions and performance on effortful tasks requiring non-visual attention, factor FD ($r = 0.109$, n.s.; Fig. 4B).

**Performance on One-back Repetition Task**

To prove the specificity of engagement of periventricular parieto-occipital regions in attention-related dot integration in cluttered point-light displays, one-back repetition task with non-camouflaged point-light configurations was administered to participants.

In patients, the miss rate was $0.127 \pm 0.131$ (mean $\pm$ SD) in responding to the canonical, and $0.109 \pm 0.123$ in responding to the scrambled configuration. In controls, the miss rate in responding to the walker was $0.025 \pm 0.026$, and in responding to the scrambled configuration it was $0.049 \pm 0.025$. Pair-wise comparison performed on the individual values of the miss rate reveals that in responding to the canonical point-light figure, patients had a significantly greater number of misses than did the controls ($t$-test, one-tailed; $P < 0.01$). No difference was found between the groups in responding to the scrambled figure ($t$-test, n.s.). Very few participants made false alarms, and there were no significant differences in the number of this type of error between the groups of participants or between distinct types of stimuli. The findings suggest that patients with PVL have difficulties integrating the local motion of dots into a cohesive percept of a point-light walking figure. This deficit is specific, and could not be accounted for simply by the general attentional imbalance because there was no difference between the patients and controls in the number of errors in responding to the scrambled figure.

In contrast to the detection task, the performance on the one-back repetition task was not related to the extent of damage to periventricular regions (Fig. 5A,B). We did not find any linkage between the percentage correct in responding to the unmasked point-light walker and the volumetric extent of PVL (Pearson product–moment correlation; $r = 0.016$, $r = -0.137$, $r = 0.123$, n.s., for the parieto-occipital, frontal and temporal regions, respectively). Overall, the findings confirm our expectation that the extent of damage to the periventricular parieto-occipital regions is tightly connected to the specific attention-related ability to integrate elements embedded in a complex array of similar distracters.

**Discussion**

The present work addresses the issue of whether periventricular parieto-occipital regions might be involved in functioning of the neural circuits driving attention-demanding visual integration of local features and elements. To this end, we investigated patients with congenital periventricular leukomalacia by using a detection task requiring an ability to integrate the local motion of elements of a point-light figure embedded in a complex array of distracters. To prove the specificity of engagement of periventricular parieto-occipital regions in attention-related visual integration, tasks on visual and non-visual attention and perceptual organization, as well as one-back...
repetition task with unmasked point-light configurations, were also administered. The outcome of the study clearly indicates that attention-related processing of point-light stimuli is compromised in patients with early bilateral periventricular parieto-occipital lesions. The degree of this impairment is substantially related to the extent of periventricular lesions in the parieto-occipital region, whereas there is no connection between detectability and the lesion extent over the frontal or temporal periventricular regions. The lack of differences in performance between former preterms without lesions and term-born participants indicates that the lower sensitivity in patients with lesions is not simply due to premature birth. Patients' performance on the one-back repetition task with unmasked point-light configurations is not related to the extent of damage over the parieto-occipital region. Therefore, the deficits in integration of dots into a cohesive percept in cluttered point-light displays appear to be connected with the filtering of distracters requiring attentional resources. Irrespective of the severity of lesions, patients have no difficulties performing effortful tasks requiring non-visual attention.

**Neural Circuits Underlying Attention-demanding Feature Integration**

Current neuropsychological and brain imaging (fMRI and PET) studies help to recognize a specific brain network that subserves attention-related integration of features and elements, and to identify the structural elements of this network involving primarily the different parts of parietal cortex (e.g. Corbetta et al., 1995; Shafritz et al., 2002; Friedman-Hill et al., 2003). Recent findings point to the recruitment of subcortical structures such as pulvinar and LGN in the functioning of this network (O’Connor et al., 2002; Ward et al., 2002; Kastner et al.,

Figure 4. The IQ scores plotted against the extent of PVL in the parieto-occipital region. (A) The relationship between the extent of PVL and the Perceptual Organization (PO, filled circles; Pearson product-moment correlation, \( r = -0.716, P < 0.02 \)) and the Processing Speed factors (PS, open circles; \( r = -0.614, P < 0.05 \)), and (B) the value of Freedom from Distractibility factor (FD, \( r = 0.08, \) n.s.) in patients. (C) The values of PO (filled diamonds; \( r = -0.388, \) n.s.) and PS factors (open diamonds; \( r = 0.348, \) n.s.) plotted against the volumetric ventricular extent in term-born controls. (D) The values of PO (filled triangles; \( r = -0.522, \) n.s.) and PS factors (open triangles; \( r = -0.293, \) n.s.) plotted against the ventricular extent in preterm born controls.

Figure 5. Comparison between performance on the detection task with a camouflaged walker and on the one-back repetition task with unmasked point-light walker in relation to the severity of PVL in the parieto-occipital region. (A) The sensitivity index \( A_z \) plotted against the volumetric extent of PVL (Pearson product-moment correlation; \( r = 0.711, P < 0.02 \)). (B) The relationship between performance on the one-back repetition task (percentage correct responses to the unmasked walker) and the PVL extent (\( r = -0.016, \) n.s.).
2004). The present study indicates that the parieto-occipital periventricular regions which are connected to the parietal cortex might also be important for attention-demanding integration. However, the precise nature of the subcortical-cortical interaction involved in the functioning of this system remains an open question. Periventricular damage might break the reciprocal thalamocortical interrelating impinging on posterior thalamocortical fibers (Krägeloh-Mann et al., 1999). Recent diffusion tensor imaging findings also suggest that PVL affects the posterior thalamic radiation, which connects the pulvinar and LGN to parietal cortex (Hoon et al., 2002; Behrens et al., 2003). This connection is implicated in attention-related binding of features and elements (Ward et al., 2002).

The parietal cortex has been demonstrated to engage in the neural processes underlying different types of visual attention. Overlapping pattern of parietal activation was revealed by fMRI under comparison of several types of attention and, moreover, by diverse attention-requiring visual tasks (e.g. Fink et al., 1997; Corbetta et al., 2002; Donner et al., 2002; Nobre et al., 2003). For example, Wojciulik and Kanwisher (1999) have shown that the junction of intraparietal and transverse occipital sulci and the anterior intraparietal sulcus are bilaterally activated by a number of attention-requiring visual tasks such as object matching and a non-spatial conjunction task but not by an effortful language task. These findings suggest the existence of a common neural substrate underlying multiple modes of visual attention. However, fMRI studies are entirely restricted to localization of brain areas showing increased blood-oxygenation-level-dependent activation, and fail to uncover the changes in brain activity unfolding over time. A future step toward the understanding of the specificity of neural mechanisms underlying attention-demanding integration of elements would be an analysis of time course and functional dynamic topography revealed by brain imaging techniques providing for high temporal resolution, for example, by magnetoencephalography (MEG).

**Attention-related Processing of Point-light Displays**

One of the important outcomes of the present work is that it provides further evidence for the role of visual attention in processing of point-light stimuli. Early studies proposed that point-light stimuli attract attention automatically, independently of intention or of the current task (e.g. Johansson, 1976; see also Thornton and Vuong, 2004), but more recent work has revised this idea (Cavanagh et al., 2001; Vaina et al., 2001; Battelli et al., 2003). For example, when attention is captured by another task administered simultaneously, top-down biological motion processing fails almost completely (Thornton et al., 2002).

Brain imaging (PET and especially fMRI) data indicate the engagement of parietal cortical regions (e.g. anterior portion of IPS, superior parietal lobule — Brodmann area 7), the lateral cerebellum and amygdala in processing of point-light displays (Bonda et al., 1996; Grossman et al., 2000; Grèzes et al., 2001; Vaina et al., 2001; Pavlova et al., 2004). These regions are also recruited in deployment of visual attention (Kastner and Ungerleider, 2001). Furthermore, it is remarkable that the fMRI findings on point-light biological motion are not congruent, and the areas of activation do not entirely overlap (Servos et al., 2002; Beauchamp et al., 2003; Puce and Perrett, 2003; Saygin et al., 2004). It appears that the topographical pattern of activation during perception of point-light biological motion is strongly affected, among other factors, by attention-related task demands. For example, even in the same sample of participants, both the magnitude and the topographical pattern of fMRI activation in response to a point-light walker are influenced by the attention-related task requirements (Vaina et al., 2001). Our earlier findings obtained by using a 151-channel entire-brain MEG system indicate that oscillatory gamma brain activity in healthy adults exhibits specific patterns of enhancements in response to point-light stimuli (Pavlova et al., 2004). A point-light walker robustly elicits the consecutive peaks of evoked oscillatory MEG activity (25–50 Hz) over the left occipital (100 ms), both parietal (150 ms) and right temporal (170 ms) lobes. The pattern of activity, however, occurs only when the point-light walker is being attended. The gamma response to an ignored point-light walker was restricted to the left parieto-occipital junction (Pavlova et al., 2000).

Patients with bilateral damage to the superior parietal lobe (Brodmann areas 7 and 40, which is a part of posterior attentional system; Posner and Dehaene, 1994) and the underlying white matter are unable to identify moving point-light walkers embedded in an array of static or moving random-dot distractors, although they have no difficulties in perceiving point-light figures per se (Schenk and Zihl, 1997). They also demonstrate an intact ability to segment the figures from the stationary background, and have normal motion-coherence thresholds. Motion-blind patient LM with bilateral lesions affecting the lateral parieto-temporo-occipital cortex and the underlying white matter demonstrates an intact ability in recognition of point-light figures presented against static noise which is much less distracting than dynamic noise (McLeod et al., 1996). Patients with unilateral (left or right) parietal lesions have difficulties in visual search for a point-light walker presented together with similar distracters (Battelli et al., 2003).

Overall, the data presented here extend the previous findings pointing to the role of periventricular parieto-occipital regions in the processing of cluttered point-light biological motion stimuli. The periventricular parieto-occipital regions might be a part of a distributed network recruited in deployment of the posterior visual attentional system. The functioning of this system seems to be vulnerable to bilateral periventricular damage even if it occurs very early in the course of brain development.

**Notes**

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