

Article Title

The Role of the Posterior Parietal Cortex in Stereopsis and Hand-eye Co-ordination during Motor Task Behaviours

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Abstract

The field of 'Neuroergonomics' has the potential to improve safety in high-risk operative environments through a better appreciation of the way in which the brain responds during human-tool interactions. This is especially relevant to Minimally Invasive Surgery (MIS). Amongst the many challenges imposed on the surgeon by traditional MIS (laparoscopy), arguably the greatest is the loss of depth perception. Robotic MIS platforms on the other hand provide the surgeon with a magnified three-dimensional view of the environment, and as a result may offload a degree of the cognitive burden. The posterior parietal cortex (PPC) plays an integral role in human depth perception. Therefore, it can be hypothesized that differences in PPC activation between monoscopic and stereoscopic vision may be observed. In order to investigate this hypothesis, the current study explores disparities in PPC responses between monoscopic and stereoscopic visual perception to better de-couple the burden imposed by laparoscopy and robotic surgery on the operator's brain. 14 participants conducted tasks of depth perception and hand-eye co-ordination under both monoscopic and stereoscopic visual feedback. Cortical haemodynamic responses were monitored throughout using optical functional neuroimaging. Overall, recruitment of the bilateral superior parietal lobule (SPL) was observed during both depth perception and hand-eye co-ordination tasks. This occurred contrary to our hypothesis, regardless of the mode of visual feedback. Operator technical performance was significantly different in 2 and 3-dimensional visual displays. These differences in technical performance do not appear to be explained by significant differences in parietal lobe processing.

Keywords: Functional Near Infrared Spectroscopy; Posterior Parietal Cortex; Minimally Invasive Surgery; Stereoscopic Visual Perception

1 Introduction

The field of ‘Neuroergonomics’ (Parasuraman, 2003) provides improved safety in high-risk leading information about human brain responds during human-tool interactions. Subtle variations in the operator’s ergonomic set-up can be evaluated to determine the configuration that best maximises neural efficiency and operator performance (Hitchcock, et al., 2003; James, et al., 2011). This is especially relevant to surgical selection in Minimally Invasive Surgery (MIS) in which complex technologies are utilised to minimise body trauma and improve patient outcomes (McMahon, et al., 1994) increasing the operator’s cognitive load. Of the many cognitive challenges placed on the surgeon by laparoscopy, the loss of depth perception is arguably the greatest, forcing the surgeon to perceptually reconstruct a three-dimensional scene from monoscopic visual clues alone. Robotic MIS systems potentially offload a proportion of the cognitive burden by providing the surgeon with a high definition three-dimensional visual display of the operative scene. Certain robotic ‘*master*’ units, at which the operator is seated, are capable of switching between monoscopic and stereoscopic visual displays and thereby facilitate systematic investigation of the operator’s brain response to monoscopic and stereoscopic stimulation (Figure 1). This is particular relevant by considering that during a controlling hand movement subjects rely more on binocular than monocular cues when both are presented (Knill 2005).

Functional brain imaging studies have been successfully performed in surgeons using sensor-based cranial imaging techniques (e.g. electroencephalography, functional near-infrared spectroscopy (fNIRS)). These studies were not specific to visual perception in surgery and instead focused on expertise-related disparity in cortical responses (Leff, et al., 2008a, 2008b, 2007; Ohuchida, et al., 2009), evolution in activation maps across sequential learning (Leff, et

al., 2008c, 2008d) and evaluation of technologies designed to stabilise MIS performance (James, et al., 2011, 2010). Moreover, studies to date have restricted their investigation to the prefrontal and frontal cortex (James, et al., 2011; Leff, et al., 2008a, 2008b, 2008c, 2007, 2006; Ohuchida, et al., 2009) with limited assessment of other cortical and sub-cortical brain regions (Leff, et al., 2008d), possibly due to the challenges associated with obtaining recordings from deeper brain areas in moving subjects performing complex procedures within real-world environments.

In this context, one particular region of interest is the posterior parietal cortex (PPC) which has been demonstrated to be integral for spatial tracking (Culham and Kanwisher, 2001; Mellet, et al., 1995; Sack, et al., 2002; Ungerleider and Haxby, 1994), attention (Corbetta, et al., 2000, 1993; Hopfinger, et al., 2000) and visuomotor control of reaching movements (Buneo and Andersen, 2006), all of which are necessary for safe operator-tool interactions. Additionally, the PPC is known to be involved in the stereoscopic vision (Sack, 2009).

Even if we are aware that the computing of depth based on stereoscopy are not only found in PPC (e.g., Shikata, et al. 1996) but also in early occipital areas (striate cortex) (e.g., Anzai, et al. 1999) only PPC was monitored in this study. As below reported, this is due to its strong involvement in the dorsal stream and, consequently, to its relevant role in tasks which required to elaborate and define, visually, the depth of objects to act on them (Milner and Goodale 2008).

The visual system has been defined as consisting of two main subsystems, the ventral and dorsal stream (Milner and Goodale 1995). The two subsystems originate from the primary visual area (V1) and project ventrally to the inferotemporal cortex (ventral stream) and dorsally

to the PPC (dorsal stream), respectively (Creem and Proffitt 2001; Milner and Goodale 2008). Both the streams process information about the features of the objects and their localization in the space, and also are both engaged for attentional effects. The main difference between the two streams is in the way the visual information is processed and transmitted (Milner and Goodale 2008). The ventral stream transforms the visual inputs in perceptual representations, which enable us to think about objects and events in the environment, and is suggested to be mainly involved in the computation of the relative disparity (e.g., the spatial relation between two objects) (Parker 2007). The dorsal stream is mainly involved in elaborating the visual inputs to mediate the visual control of skilled actions directed at the external environment (Milner and Goodale 2008), and in the computation of stereo depth, which is based on a direct computation of the binocular correlation between the images captured by the left and right eyes (Minini et al. 2010; Parker 2007).

Furthermore, evidence from lesion and non-invasive human brain mapping studies suggests that the spatial and attentional functions of the PPC may be segregated between superior parietal lobule (SPL) and inferior parietal lobule (IPL). The SPL is involved in computing target positions in the egocentric reference frame for the immediate control of reaching, grasping and eye-movements (visually guided movement of arms toward a goal) and is suggested to be one of the higher centres involved in stereopsis (Sack, 2009). Studies using functional Magnetic Resonance Imaging (fMRI) have demonstrated that stereopsis leads to activations within both the occipital lobe and SPL (Nishida, et al., 2001). On the other hand, the IPL plays an important role in sustained attention and to aid the detection of salient stimuli (Sack, 2009). Beside that, IPL is engaged in space perception (Rizzolatti and Matelli 2003), in action planning (Jubault, et al. 2007) and for the encoding (Koechlin, et al. 2002), storage (Wu, et al.

2004), execution (Bengtsson, et al. 2004) and representation of action sequences (Behrmann, et al. 2004).

Therefore, through the functions of the SPL and IPL, the posterior parietal cortex may be important in decoding visuospatial information (e.g., visually guided movements and spatial localization of objects in the space) to aid accurate instrument manipulation during robotic MIS. Moreover, there is evidence that parietal lobe (PL) activation may correlate with subject performance (Todd and Marois, 2005; Walter and Dassonville, 2011). Finally, there is evidence suggesting a relationship between spatial cognition, performance and parietal activation (Carpenter, et al., 1999; Ng, et al., 2001; Tagaris, et al., 1996, Vannini, et al., 2004).

In the current investigation, a group of subjects was recruited to perform a series of tasks on a ‘master-slave’ robotic surgical platform. These included assessments of ‘depth perception’ and ‘hand-eye co-ordination’ under monoscopic and stereoscopic visual feedback. Parietal lobe function was monitored throughout, enabling the visuospatial cognitive challenges between laparoscopic and robotic MIS to be compared. Furthermore, cortical activation was investigated by means of the fNIRS neuroimaging technique. Compared to other neuroimaging techniques, fNIRS permits serial assessment of tasks in realistic environments in subjects performing complex dynamic movements (Perrey 2008). These characteristics make fNIRS a convenient modality for investigating cortical activation during complex tasks in MIS.

In this investigated context a higher activation on the PPC during stereoscopic visual condition with respect to the monoscopic may be expected. Given the relative importance of the SPL in stereopsis as defined above, greater SPL activation was anticipated during trials conducted in the stereoscopic visual mode. Furthermore, complex bimanual co-ordination tasks (i.e.

visuomotor tasks) were expected to burden the PPC to a greater extent than tasks requiring depth perception without motor involvement (i.e. assessment of visual depth perception). In this regard, the hypothesis to be tested was that hand-eye co-ordination tasks would lead to a greater activation across the SPL and IPL, due to its involvement in the dorsal stream and action planning, with respect to the tasks of visual depth perception. These results bring also a direct comparison of the PPC activation during visual depth perception and hand-eye co-ordination tasks under stereoscopic and monoscopic visual conditions. However, activation in the PPC is expected for the depth perception task due to engagement of the IPL on the spatial localization of stimuli (space perception). Finally, it was hypothesised that the magnitude of PPC activation may predict operator performance during depth perception and hand-eye co-ordination tasks.

2 Materials and Methods.

In order to elucidate PPC excitation during visuospatial and visuomotor stimulation two experiments were conducted (referred to henceforth as Experiment I and Experiment II). Experiment I (object depth perception) aimed to investigate the extent of PPC activation induced by visuospatial depth perception and Experiment II (hand-eye co-ordination) assessed PPC activation during a robot-assisted hand-eye co-ordination (visuomotor) task. To evaluate the way in which rendering of the visual stimulus influenced PPC engagement and behavioural performance, experimental tasks were conducted under both the monoscopic and stereoscopic view.

2.1 Participants

14 (3 females) healthy right-handed subjects (mean age \pm SD = 25.5 \pm 5 years) with normal or corrected to normal vision were recruited. All subjects were task naïve and were recruited from

Imperial College London, United Kingdom (UK). Subjects had no prior history of neuropsychological disease(s). All the participants performed the two experiments under both monoscopic and stereoscopic visual feedback. Only three participants had previous experience of the robotic surgical system used for the experiments. Written informed consent was obtained from each participant prior to enrolment. Subjects were asked to refrain from caffeine intake 24 hours prior to the experiment.

2.2 Apparatus

2.2.1 Optical Imaging Equipment

For the current experiment the Functional Near Infrared Spectroscopy (fNIRS) ETG-4000 (Hitachi Medical Corp., Japan) Optical Topography system was employed using a 3 x 3 arrangement of optodes consisting of 10 emitters and 8 detectors resulting in the detection of relative changes in cortical haemodynamics at 24 different loci (-channels). The 3 x 3 optodes arrangement is illustrated in Figure 2..

Functional Near Infrared Spectroscopy (fNIRS) is a neuroimaging modality capable of evaluating the cortical function through the detection of relative changes in oxygenated (HbO₂) and deoxygenated (HHb) haemoglobin concentrations as a proxy of neural activity. The main advantages of the fNIRS modality are tolerance to motion artefacts, and high portability (Bunce, 2006). The main disadvantages of fNIRS are low penetration depth (only cortical function in a depth of maximum 2-4 mm can be investigated) and a relatively low temporal resolution ($\leq 100\text{Hz}$) (Ferrari and Quaresima, 2012). However, these disadvantages are not preventing the measurement of changes in the brain blood flow due to neural activity.

2.2.2 Robotic System

In this study the ‘da Vinci’ robotic system (Intuitive Surgical Inc., Mountain View, CA) was used to perform complex motor tasks under both monoscopic and stereoscopic visual display modalities.

The ‘da Vinci’ system is a comprehensive master-slave surgical robot and consists of: (1) an surgeon's console; (2) a patient cart with four interactive robotic arms; (3) a high-performance vision system; and (4) patented *EndoWrist* instruments (Intuitive Surgical, 2012). Robotic systems such as the ‘da Vinci’ offer several advantages when compared to standard laparoscopy including: (i) increased fine manual dexterity with motion scaling and tremor stabilisation; (ii) improved ergonomic position, aiding the surgeons’ comfort by allowing them to operate from a seated position and (iii) improved visualization with image stereopsis (Kwok, et al., 2012; Rockall and Darzi, 2003). The benefit of the three-dimensional video-imaging systems in MIS has been proved under different experimental conditions (e.g., (Kong, Oh et al. 2010; Storz, et al. 2012)). The main drawbacks of the Da Vinci system are its high cost and the high training required to the surgeons to use this device.

2.3 Experimental Set-Up and Study Design

Both experiments were conducted at Imperial College London (Imperial College London, 2012). Recruited subjects from staff and students of Imperial College were seated comfortably at the ‘da Vinci’ master console whilst two researchers (GP and DRL) positioned the ETG-4000 channels over the bilateral parietal lobes as illustrated in Figure 3. A configuration of two 3x3 probe arrays was used (Figure 2), with each array capable of measuring relative changes in cortical haemodynamics in 12 regions of the PL. Optodes were secured in thermoplastic holders (inter-optode distance 30 mm) and fastened to the participant's head using a bandage in order to

minimise optode movement artefacts. Optodes were placed bilaterally over the PPC according to the International 10-20 system of electrode placement (Jasper, 1958). One 3x3 array was centred on P3 (left hemisphere) and the other on P4 (right hemisphere), as illustrated in Figure 2. As illustrated in Figure 3 optode arrays were positioned such that channels 3 and 10 were located approximately on P2 and P6 and channels 17 and 20 were located approximately on P1 and P5 of the unambiguously illustrated (UI) 10/5 system (Jurcak, et al., 2007). The likely cortical projection points of the cranial markers P3 and P4 (UI 10-20 system) are the right and left SPL (Okamoto, et al., 2004), as predicted by the Talairach Daemon program (Lancaster, et al., 2000). In this study, the probabilistic cortical projection points (expressed in MNI coordinates) of P3 and P4 are based on the Okamoto et al. work (Okamoto, et al., 2004). P3 location of the international 10-20 cortical projection point: -39.5, -76.3, 47.4 (xyz). P4 location of the international 10-20 cortical projection point: 36.8, -74.9, 49.2 (xyz).

Participants were instructed to regard the screen of the master console for the entire duration of the experiment. The workspace where the stimuli were presented was illuminated by a dual light source and the scene was recorded by dual cameras oriented obliquely or perpendicularly with respect to the platform as illustrated in Figure 3. Experimental tasks were conducted in a block design consisting of ten blocks (five for each visual feedback) with each block comprising alternating episodes of 'rest' (30s) and 'task' (variable temporal duration). During rest periods subjects were asked to close their eyes and relax. Unlike rest periods which were of fixed duration, the temporal duration of task episodes were determined by the investigators based on appropriate task completion. Participants performed the experiments under both monoscopic and stereoscopic visual feedback. These modes of visual feedback were randomised in order to account for any learning effects.

2.3.1 Experiment I: object depth perception (ODP)

Stimuli consisted of nine different size wood spheres arranged at different elevations and locations (depths from viewpoint) on a platform positioned within the 'da Vinci' workspace, as illustrated in Figure 4. The depth of the spheres varied from 0.8 to 4 cm from the platform surface. The diameters of the spheres were randomly selected between 6, 8 and 10 mm, to avoid object size being used as a depth cue. The platform was made of wood and painted in black to reduce shadow as well as reflectance on the surface of the spheres. Five different platforms were used. Size, depth and position of the nine spheres were randomized within and between platforms. Each subject viewed all five platforms but the order of platform visualisation was randomised. During the rest condition, a researcher selected a new platform at random and placed it within the workspace. The task blocks had a mean temporal duration of 18.49s (standard deviation 14.39s) in the monoscopic visual condition and a mean temporal duration of 14.03s (standard deviation 7.44s) in the stereoscopic visual condition.

Subjects were instructed to verbally indicate the nearest and farthest sphere in the platform as perceived through the 'da Vinci' console. Subjects' responses were recorded by a researcher and depth perception accuracy was determined (percentage of correct responses).

2.3.2 Experiment II: hand-eye co-ordination (HEC)

For the hand-eye co-ordination task, a platform consisting of twelve rubber coloured cones was used as illustrated in Figure 4 (in the bottom). The task required the operator to move an elastic band between three coloured cones using the robotic graspers. Subjects were instructed to manipulate the band between the robotic graspers, and then place it onto each cone in a predefined sequence (Figure 4). Subjects were allowed a brief familiarisation session prior to

positioning the fNIRS optodes. All trials were videotaped for retrospective review and performance analysis. Technical performance was determined by counting the number of ‘errors’ according to criteria defined by experts. Table 1 highlights the actions considered to be erroneous, and Figure 5 illustrates examples of common errors in hand-eye co-ordination. Two independent observers reviewed the videotapes and retrospectively scored performance against the operation specific checklists defined in Table 1, which resulted in objective scores for hand-eye co-ordination and technical skills.

The task blocks had a mean temporal duration of 67.66s (standard deviation 24.16s) in the monoscopic visual condition and a mean temporal duration of 50.58s (standard deviation 13.72s) in the stereoscopic visual condition.

2.4 Brain haemodynamic data processing and analysis

A group-level analysis was performed on both performance and functional brain data.

Regarding brain data, hypothesis testing was utilised as implemented in the NIRS Statistical Parametric Mapping (NIRS-SPM) (Ye, et al., 2009). NIRS-SPM provides the activation pattern following within-group analysis for HbO₂ and HHb. In the current study, a hemodynamic response function (HRF) was used and the Sun's Tube Correction (Cao and Worsley 1999; Sun 1993) was applied for statistical correction to account for multiple comparisons and a level of 0.05 was accepted as statistically significant. Excitation was considered to be statistically significant if task-evoked increases in HbO₂ were coupled to decreases in HHb.

Furthermore, the comparative analysis of the variable ΔHb (average task Hb – average rest Hb) between monoscopic and stereoscopic conditions was performed. Data was low pass filtered

(decimated) to reduce systemic influence, detrended to eliminate drift and integrity checked for saturation related problems (a total of 16 data were removed, i.e. subject 9 channel 1).

The spatial registration of the NIRS channels has been performed without using a 3D digitizer. The MNI coordinates of P4 and P3 (international 10-20 cortical projection points (Okamoto, et al., 2004)) were selected as the reference points on the scalp. During both the experiments the center optodes (emitter 13 on the left and emitter 18 on the right) were aligned with P3 and P4 (Figure 2). Then, the channels coordinated were manually extracted.

3 Results

NIRS-SPM approach highlighted caudal SPL excitation in both stereoscopic and monoscopic visual conditions, suggesting that the trend towards PPC activation seems to be independent of the mode of visual stimulation, or that fNIRS is unable to discern subtle differences at its current technological state.

3.1 Experiment I: Object Depth Perception

3.1.1 Brain activity analysis

Figure 6 provides the activation pattern for the object depth perception experiment. In the monoscopic visual condition results suggest statistically significant activation within the SPL [channels 6, 8, 9 and 11 in RH and channels 21, 22 and 24 in LH]. In contrast, a trend towards activation was observed amongst few channels centred on the IPL [channel 23 in LH]. Similar to the results obtained for monoscopic stimulation, in the stereoscopic visual conditions significant bilateral SPL activation was demonstrated [channels 4, 6, 8 and 9 in RH and channels 19, 21, 24 in LH]. However, cortical haemodynamic changes in channels located over

the IPL did not reach statistical threshold. Overall, the analysis technique demonstrates the recruitment of the SPL bilaterally during the object depth perception task regardless of the mode of visual feedback.

Furthermore, the comparative analysis of the variable ΔHb (average task Hb – average rest Hb) reached no significant statistical difference (Wilcoxon Sign Rank Test, $p < 0.05$) in the PPC activity between monoscopic and stereoscopic conditions for all the investigated channels.

3.1.2 Performance analysis

Compared to the monoscopic view, stereoscopy resulted in improved technical performance (mean error score: monoscopy=77%, stereoscopy=11%, $p < 0.05$). Comparing PPC activity and performance in the object depth perception task, no statistically significant correlation could be observed. Correlation was not observed irrespectively of the channel and perceptual condition (Spearman's Rank Correlation, ($p < 0.05$)).

3.2 Experiment II: Hand-eye co-ordination

3.2.1 Brain activity analysis

Figure 7 illustrates the PPC activation pattern for Experiment II in both visual conditions. Results suggest activation of caudal SPL channels in both monoscopic and stereoscopic visual conditions. In the monoscopic visual condition a focused area of activation, located caudally on the SPL [channels 6, 9, 11 in RH and 16, 21 and 24 in LH] was revealed. In the stereoscopic visual condition NIRS-SPM analysis revealed relative homogeneity in terms of the spatial location of activation foci regardless the mode of visual feedback.

As for Experiment I, the values of ΔHb (average task Hb – average rest Hb) between monoscopic and stereoscopic conditions were compared. No significant statistical difference was reached in the PPC activity between monoscopic and stereoscopic conditions for all the investigated channels (Wilcoxon Sign Rank Test, $p < 0.05$).

3.2.2 Performance analysis

The average number of errors was observed to be lower in stereoscopic mode versus monoscopic mode [mean (range): stereoscopic=48 (31.5-71.5); monoscopic=67 (46.5-88), $p < 0.05$]. As for Experiment I, no statistically significant correlation was observed between the PPC activity and technical skill on the hand-eye co-ordination task (Spearman's Rank Correlation, ($p < 0.05$)). Correlation was not found neither of the modes of visual rendering and for any channel.

3.3 Depth Perception versus Hand-Eye Co-ordination

A statistical test has been applied to investigate the effect of both the experimental conditions (hand-eye co-ordination and object depth perception) and visual conditions (2D and 3D) on the PPC activation. The variable ΔHb (average task Hb – average rest Hb) was tested using a non-parametric alternative for the repeated measures ANOVA (Friedman test, $p < 0.05$). Both variations in HbO_2 and HHb were investigated.

For the signal HbO_2 statistical significant differences for the channels 2, 3, 4, 6, 8, 9, 11, 15, 16, 18, 19, 22 were observed. For the signal HHb statistical significant differences for the channels 8, 10, 11, 13, 15, 20, 21, 22, 23 were observed. In table 2 the corresponding p-values are reported.

To determine which conditions significantly differed from each other a post-hoc analysis (Wilcoxon signed rank test) using a Holm's sequential Bonferroni correction was performed at a 0.0083 level of significance for the smallest p-value, a 0.01 level of significance for the second smallest p-value, and so on.

As reported in the previous section, no significant difference has been found between the monoscopic and stereoscopic visual conditions in Experiment I and in Experiment II for both HbO₂ and HHb. Nevertheless, significant differences in parietal lobe excitation were observed comparing depth perception with hand-eye co-ordination (i.e. action) when evaluated under the same visual condition (i.e. either mono- or stereo).

Table A1 highlights the results of the post-hoc analysis for the HbO₂ signal. In the monoscopic visual condition, a significant difference between the hand-eye co-ordination and object depth perception experiment was reported for the channels 6, 8, 9, 15, 16, 18, 19 and 22. Additionally, the highest Δ HbO₂ values were observed for the hand-eye co-ordination experiment (Table A3) for all the channels except channels 5, 20 and 23 (which are located on the IPL). In the stereoscopic condition, the highest Δ HbO₂ values were observed in the hand-eye co-ordination experiment (Table A3) for all the channels except channels 2, 5 and 22 (the last two channels are located in IPL). Additionally, in the stereoscopic condition, the post-hoc correction analysis demonstrates a significant difference for the channels 3, 6, 9, 15 and 22. For certain channels post-hoc analysis did not reveal significant between-condition effects (channels 2,4 and 11).

Table A2 provides the results of the post-hoc analysis for the HHb signal. In the monoscopic visual condition a significant difference between the two experiments was observed for the

channels 13, 15, 20, 21 and 23. Among these, the lowest delta HHb values were reported for the channel 13 and 15 for the object depth perception experiment and for the channels 20, 21 and 23 for the hand-eye co-ordination experiment (Table A4). In the stereoscopic visual condition, a significant difference between the two experiments was observed for channel 15 (lower delta HHb value for the object depth perception experiment). The post-hoc analysis was not able to determine which conditions significantly differed from each other for channel 8, 10 and 11.

4 Discussion

This study was designed to explore the disparities in parietal responses between monoscopic and stereoscopic visual perception in order to better de-couple the challenges imposed by laparoscopy versus robotic surgery on centres of spatial processing in the operator's brain.

The primary finding was that for tasks of object depth perception and hand-eye co-ordination, broad spatial coherence in the location of activation foci was observed regardless the mode of visual feedback. Specifically, the SPL and, to a lesser extent, the IPL were observed to be activated at a similar degree in both monoscopic and stereoscopic perceptual conditions. The findings remain contrary to the original hypothesis; given the relative importance of the SPL in 3D perception (Nishida, et al., 2001), greater activation in this region would be anticipated during trials conducted under stereoscopic visual feedback.

Spatial overlap in cortical maps between 2D and 3D depth perception has been observed previously (Merboldt, et al., 2002). In the study by Merboldt et al. (Merboldt, et al., 2002) 2D and 3D percepts led to a certain degree of overlap between activation in higher order visual areas. In a similar study, brain areas of nearly identical activation were observed during monoscopic and stereoscopic depth perception, which included parietal areas Brocca Areas

(BA) 7, 31, 37 and 39, and occipital areas BA18 and 19 (Fischmeister and Bauer, 2006). In the study by Fischmeister et al. (Fischmeister and Bauer, 2006) it was only upon contrast analysis that differences in the magnitude of parietal activation were observed between visual perceptual conditions. In this regard, as reported above, a further supplementary analysis was conducted upon the current dataset comparing the variable ΔHb (average task Hb – average rest Hb) between monoscopic and stereoscopic conditions for both experiments. No significant statistical difference was reached in the PPC activity between monoscopic and stereoscopic conditions.

Therefore, despite mounting evidence suggesting that stereoscopy leads to greater activation in higher visual centres and the parietal cortex, this remains unproven with fNIRS. Unlike the current study, other fNIRS investigations of stereopsis have observed differences between 2D and 3D viewing (e.g. checker board with horizontal disparity) (Wijeakumar, et al., 2012). However, differences in cortical behavior were observed only in the visual cortex (O1, O2, International 10-20 system) and not in the parietal cortex. Whilst the latter findings parallel the current analysis, more detailed comparisons between these studies is challenging owing to differences in the paradigm (i.e. checkerboard stimulation versus object depth identification), experimental design (e.g. fixed block versus variable block design) and imaging equipment (i.e. OT versus combined OT-EEG).

The current analysis implicates the SPL and, to a lesser extent, the IPL in tasks that require object depth perception and hand-eye co-ordination. In this regard, the SPL is known to play an important role in spatial task performance when spatial processing is required, especially in hand-eye co-ordination tasks. IPL is known to be engaged in action planning and space perception. Accordingly, a greater activation was observed during the hand-eye co-ordination

task than the object depth perception task. These results contribute to explore PPC activation differences between motor and perceptual tasks under stereoscopic visual conditions and between monoscopic and stereoscopic visual condition during actions.

One explanation for the comparatively attenuated IPL response is that the temporo-parietal junction (TPJ) was observed to be activated during both rest and task conditions. Accordingly, IPL activation may not be related to task execution. Behrmann et al. (Behrmann, et al., 2004) proposed that the TPJ is activated in response to potentially novel events when subjects are engaged in a neutral behavioural context (e.g., not performing any task). Such activation is observed independently of the sensory modality (auditory, tactile and visual) in which the input is delivered (Downar, et al., 2002). The IPL and the TPJ seem to be the source of a continuous signal to actively maintain the new attentive state, whereas the SPL seems to be the source of a brief attentional control signal to shift between attentive states (Moran and Desimone, 1985; O'Craven, et al., 1997). In this context it is plausible that activation of the IPL occurs during the 'rest' condition, whereas activation of SPL occurs in response to task-evoked changes in attentional demands.

A different hypothesis is needed to explain why the rostral SPL appears to activate to a lesser extent than the caudal SPL. One possible explanation is that the channels located rostrally on the SPL are not responding to the visuospatial processes but rather to the somatosensory input. Indeed, the somatosensory cortex, whose role it is to discriminate somatosensory information, is located rostrally on the SPL and IPL. Considering that the somatosensory cortex receives important sensory feedback pertaining to temperature, touch, proprioception and nociception (Kandel et al., 2000), it is conceivable that observed activation in this region relates to the sensory information flow and not the task. Consequently, the somatosensory cortex may be

active during both rest and task conditions reducing the chances of detecting differences in cortical haemodynamic changes between task and rest conditions.

These results could place arguments in favour of a type II error. The complexity of the tasks could have introduced uncontrolled variables (i.e., high cognitive workload) and the limited penetration depth and temporal resolution of the NIRS system could have bounded the discrimination of subtle differences. Additionally, the applied analysis methods could be not powerful enough and the number of subjects investigated not high enough to detect a difference in the brain activation through group data analysis. Nevertheless, results suggest a greater activation in the PPC, especially in the SPL, for the hand-eye co-ordination than in the object depth perception task for both the visual conditions.

5 Conclusions

In summary, the results support SPL activation during object depth perception and hand-eye co-ordination that are involved during robotic surgical manipulation. Overall, the extent of parietal activation does not appear to be dependent upon the mode of visual rendering despite significant differences in operator performance. However, a significant difference in the PPC activation was observed between the hand-eye co-ordination and depth perception task. The disparity between laparoscopy and robotic surgery on the operator's cognitive burden has not been disambiguated or de-coupled.

Funding statement

This research was funded in part by the Academy of Medical Sciences and Cancer Research (UK), which was not involved in the in study design, in the collection, analysis and interpretation of data.

Conflict of Interest

None to declare

References

Anzai, A., Ohzawa I., and Freeman R. D. (1999) Neural mechanisms for processing binocular information I. Simple cells. *Journal of Neurophysiology* 82(2): 891-908.

Behrmann, M., Geng, J. J., Shomstein, S. (2004) Parietal cortex and attention. *Current opinion in neurobiology*, 14 (2), 212-217.

Bengtsson, S. L., Ehrsson, H. H. , Forssberg H, Ullén F. (2004) Dissociating brain regions controlling the temporal and ordinal structure of learned movement sequences. *European Journal of Neuroscience* 19(9): 2591-2602.

Bunce, S. (2006) Functional near-infrared spectroscopy. *Engineering in Medicine and Biology Magazine, IEEE*, 25 (4), 54-62.

Buneo, C.A., Andersen, R.A. (2006) The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements. *Neuropsychologia*, 44, 2594-2606.

Cao, J. and K. Worsley (1999). "The geometry of the Hotelling's T2 random field with applications to the detection of shape changes." *Ann. Stat* 27(3): 925-942.

Carpenter, P.A., Just, M. A., Keller, T. A., Eddy, W., Thulborn, K. (1999) Graded functional activation in the visuospatial system with the amount of task demand. *Journal of Cognitive Neuroscience*, 11 (1), 9-24.

Corbetta, M., Kincade, J. M., Ollinger, J.M., McAvoy, M.P., Shulman, G.L. (2000) Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature neuroscience*, 292-297.

Corbetta, M., Miezin, F.M., Shulman, G.L., Petersen, S.E. (1993) A PET study of visuospatial attention. *The Journal of Neuroscience*, 13 (3), 1202-1226.

Creem, S. H. and Proffitt, D. R. (2001) Defining the cortical visual systems: , "what", "where" and , "how". *Acta Psychologica* 107(1): 43-68.

Culham, J.C., Kanwisher, N.G. (2001) Neuroimaging of cognitive functions in human parietal cortex. *Current opinion in neurobiology*, 11, 157-163.

Downar, J., Crawley, A. P., Mikulis, D. J., Davis, K. D. (2002) A cortical network sensitive to stimulus salience in a neutral behavioral context across multiple sensory modalities. *Journal of neurophysiology*, 87 (1), 615-620.

Ferrari, M. and Quaresima, V. (2012) A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *Neuroimage*, 63(2): p. 921-935.

Fischmeister, F., Bauer, H. (2006) Neural correlates of monocular and binocular depth cues based on natural images: A LORETA analysis. *Vision research*, 46 (20), 3373-3380.

Hitchcock, E. M., Warm, J. S., Matthews, G., Dember, W. N., Shear, P. K., Tripp, L. D., Mayleben, D.W., Parasuraman, R. (2003) Automation cueing modulates cerebral blood flow and vigilance in a simulated air traffic control task. *Theoretical Issues in Ergonomics Science*, 4 (1-2), 89-112.

Hopfinger, J., Buonocore, M., Mangun, G. (2000) The neural mechanisms of top-down attentional control. *Nature neuroscience*, 3, 284-291.

Imperial College London (2012) The Hamlyn Centre. Retrieved from <http://www3.imperial.ac.uk/roboticsurgery>

Intuitive Surgical (2012) The da Vinci Surgical System. Retrieved from http://www.intuitivesurgical.com/products/davinci_surgical_system/

James, D. R., Orihuela-Espina, F., Leff, D. R., Sodergren, M. H., Athanasiou, T., Darzi, A., Yang, G.Z. (2011) The ergonomics of natural orifice transluminal endoscopic surgery (NOTES) navigation in terms of performance, stress, and cognitive behavior. *Surgery*, 149 (4), 525-533.

James, D.R., Orihuela-Espina, F., Leff, D.R., Mylonas, G., Kwok, K. W., Darzi, A., Yang, G.Z. (2010) Cognitive burden estimation for visuomotor learning with fNIRS. *MICCAI 2010 Beijing, Spring*, pp. 319-326.

Jasper, H. H. (1958) The ten twenty electrode system of the international federation. *Electroencephalography and clinical neurophysiology*, 10, 371-375.

Jubault, T., Ody C., Koechlin E. (2007) Serial organization of human behavior in the inferior parietal cortex. *The Journal of Neuroscience* 27(41): 11028-11036.

Jurcak, V., Tsuzuki, D., Dan, I. (2007) 10/20, 10/10, and 10/5 systems revisited: their validity as relative head-surface-based positioning systems. *Neuroimage*, 34 (4), 1600-1611.

Kandel, E.R., Schwartz, J.H., Jessell, T.M. (2000) Principles of neural science. New York: McGraw-Hill.

Knill, D. C. (2005). Reaching for visual cues to depth: The brain combines depth cues differently for motor control and perception. *Journal of Vision* 5(2).

Koechlin, E., Danek A., Burnod Y., Grafman J. (2002) Medial prefrontal and subcortical mechanisms underlying the acquisition of motor and cognitive action sequences in humans. *Neuron* 35(2): 371-381.

Kong S.H., Oh B.M., Yoon H., Ahn H.S., Lee H.J., Chung S.G., Shiraishi N., Kitano S., Yang HK. (2010) Comparison of two-and three-dimensional camera systems in laparoscopic performance: a novel 3D system with one camera. *Surgical endoscopy* 24(5): 1132-1143.

Kwok, K., Sun, L., Mylonas, G., James, D.R., Orihuela-Espina, F., Yang, G.Z. (2012) Collaborative Gaze Channelling for Improved Cooperation During Robotic Assisted Surgery. *Annals of Biomedical Engineering*, 1-12.

Lancaster, J., Woldrff, M., Parsons, L., Liotti, M., Freitas, C., Rainey, L., Kochunov, P., Nickerson, D., Mikiten, S., Fox, P. (2000). Automated Talairach atlas labels for functional brain mapping. *Human brain mapping*, 10 (3), 120-131.

Leff, D. R., Elwell, C. E., Orihuela-Espina, F., Atallah, L., Delpy, D. T., Darzi, A., Yang, G.Z. (2008a) Changes in prefrontal cortical behaviour depend upon familiarity on a bimanual co-ordination task: an fNIRS study. *Neuroimage*, 39 (2), 805-813.

Leff, D. R., Leong, J. J., Aggarwal, R., Yang, G. Z., Darzi, A. (2008b) Could variations in technical skills acquisition in surgery be explained by differences in cortical plasticity. *Annals of surgery*, 247 (3), 540-543.

Leff, D. R., Orihuela-Espina, F., Atallah, L., Athanasiou, T., Leong, J. J., Darzi, A., Yang, G.Z. (2008c). Functional prefrontal reorganization accompanies learning-associated refinements in surgery: a manifold embedding approach. *Computer Aided Surgery*, 13 (6), 325-339.

Leff, D. R., Orihuela-Espina, F., Leong, J., Darzi, A., Yang, G.Z. (2008d). Modelling dynamic fronto-parietal behaviour during minimally invasive surgery-a Markovian trip distribution approach. *MICCAI*. New York, Springer, pp. 595-602.

Leff, D.R., Orihuela-Espina, F., Atallah, L., Darzi, A., Yang, G. Z. (2007) Functional near infrared spectroscopy in novice and expert surgeons: a manifold embedding approach. *MICCAI 2007 Brisbane Australia*. Springer, pp. 270-277.

Leff, D.R., Koh, P., Aggarwal, R., Leong, J., Deligianni, F., Elwell, C., Delpy, D., Darzi, A., Yang, G.Z. (2006) Optical mapping of the frontal cortex during a surgical knot-tying task, a feasibility study. *Medical Imaging and Augmented Reality*, 140-147.

McMahon, A. J., Anderson, J. N., Ramsay, J. R., O'Dwyer, P. J., Russell, I. T., Ross, S., Sutherland, G., Galloway, D., Morran, C.G. (1994) Laparoscopic versus minilaparotomy cholecystectomy: a randomised trial. *The Lancet*, 343 (8890), 135-138.

Mellet, E., Tzourio, N., Denis, M., Mazoyer, B. (1995) A positron emission tomography study of visual and mental spatial exploration. *Journal of Cognitive Neuroscience*, 7 (4), 433-445.

Merboldt, K. D., Baudewig, J., Treue, S., Frahm, J. (2002) Functional MRI of self-controlled stereoscopic depth perception. *Neuroreport*, 13 (14), 1721-1725.

Milner, A. D. and Goodale M. A. (1995) *The visual brain in action*. New York: Oxford.

Milner, A. D. and Goodale M. A. (2008) Two visual systems re-viewed. *Neuropsychologia* 46(3): 774-785.

Minini, L., A. J. Parker and H. Bridge (2010). "Neural modulation by binocular disparity greatest in human dorsal visual stream." *Journal of Neurophysiology* 104(1): 169.

Moran, J., Desimone, R. (1985) Selective attention gates visual processing in the extrastriate cortex. *Frontiers in cognitive neuroscience*, 229, 342-345.

Ng, V., Bullmore, E., De Zubicaray, G., Cooper, A., Suckling, J., Williams, S. (2001) Identifying rate-limiting nodes in large-scale cortical networks for visuospatial processing: an illustration using fMRI. *Journal of Cognitive Neuroscience*, 13 (4), 537-545.

Nishida, Y., Hayashi, O., Iwami, T., Kimura, M., Kani, K., Ito, R., Shiino, A., Suzuki, M. (2001) Stereopsis-processing regions in the human parieto-occipital cortex. *Neuroreport*, 12 (10), 2259-2263.

O'Craven, K. M., Rosen, B. R., Kwong, K. K., Treisman, A., Savoy, R. L. (1997) Voluntary attention modulates fMRI activity in human MT-MST. *Neuron*, 18 (4), 591-598.

Ohuchida, K., Kenmotsu, H., Yamamoto, A., Sawada, K., Hayami, T., Morooka, K., Takasugi, S., Konishi, K., Ieiri, S., Tanoue, K. (2009) The frontal cortex is activated during learning of endoscopic procedures. *Surgical endoscopy*, 23 (10), 2296-2301.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., Kohno, S., Oda, I., Isobe, S., Suzuki, T., Kohyama, K. (2004) Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10-20 system oriented for transcranial functional brain mapping. *Neuroimage*, 21, 99.

Parasuraman, R. (2003) Neuroergonomics: Research and practice. *Theoretical Issues in Ergonomics Science*, 4 (1-2), 5-20.

Parker, A. J. (2007). Binocular depth perception and the cerebral cortex. *Nature Reviews Neuroscience* 8(5): 379-391.

Perrey, S. p. (2008). "Non-invasive NIR spectroscopy of human brain function during exercise." *Methods* 45(4): 289-299.

Rizzolatti, G. and Matelli M. (2003) Two different streams form the dorsal visual system: anatomy and functions. *Experimental Brain Research* 153(2): 146-157.

Rockall, T., Darzi, A. (2003) Robot-assisted laparoscopic colorectal surgery. *The Surgical clinics of North America*, 83 (6), 1463.

Sack, A. (2009) Parietal cortex and spatial cognition. *Behavioural brain research*, 202 (2), 153.

Sack, A., Hubl, D., Prvulovic, D., Formisano, E., Zanella, F.E., Maurer, K., Goebel, R., Dierks, T., Linden, D.E.J. (2002) The experimental combination of rTMS and fMRI reveals the functional relevance of parietal cortex for visuospatial functions. *Cognitive brain research*, 13 (11), 85-93.

Shikata E., Tanaka Y., Nakamura H., Taira M., and Sakata H. (1996) Selectivity of the parietal visual neurones in 3D orientation of surface of stereoscopic stimuli. *Neuroreport* 7(14): 2389-2394.

Storz P., Buess G.F., Kunert W., Kirschniak A. (2012) 3D HD versus 2D HD: surgical task efficiency in standardised phantom tasks. *Surgical endoscopy* 26(5): 1454-1460.

Sun, J. (1993). "Tail probabilities of the maxima of Gaussian random fields." *The Annals of Probability*: 34-71.

Tagaris, G. A., Kim, S. G., Strupp, J. P., ersen, P., Ugurbil, K., Georgopoulos, A. P. (1996) Quantitative relations between parietal activation and performance in mental rotation. *NeuroReport-International Journal for Rapid Communications of Research in Neuroscience*, 7 (3), 773-776.

Todd, J. J., Marois, R. (2005) Posterior parietal cortex activity predicts individual differences in visual short-term memory capacity. *Cognitive, Affective & Behavioral Neuroscience*, 5 (2), 144-155.

Ungerleider, L., Haxby, J.V. (1994) What'and where'in the human brain. *Current opinion in neurobiology*, 4 (2), 157-165.

Vannini, P., Almkvist, O., Franck, A., Jonsson, T., Volpe, U., Wiberg, M. K., Wahlund, L.O., Dierks, T. (2004) Task demand modulations of visuospatial processing measured with functional magnetic resonance imaging. *Neuroimage*, 21 (1), 58-68.

Walter, E., Dassonville, P. (2011) Activation in a Frontoparietal Cortical Network Underlies Individual Differences in the Performance of an Embedded Figures Task. *PloS one*, 6 (7), e20742.

Wijeakumar, S., Shahani, U., McCulloch, D., Simpson, W. (2012) Neural and vascular responses to fused binocular stimuli: A VEP and fNIRS study. *Investigative Ophthalmology & Visual Science*, 53 (9), 5881-5889.

Wu, T., Kansaku K., Hallett M. (2004) How self-initiated memorized movements become automatic: a functional MRI study. *Journal of Neurophysiology* 91(4): 1690-1698.

Ye, J. C., Tak, S., Jang, K. E., Jung, J., Jang, J. (2009) NIRS-SPM: statistical parametric mapping for near-infrared spectroscopy. *Neuroimage*, 44 (2), 428-447.

Figures

Fig. 1 An example of two- and three-dimensional views of the operative scene. The dual cameras mounted on the robotic arm (bottom-left) permit the acquisition of high-resolution images of the surgical site. Pressing a button on the master console the visual display can be switched between monoscopic and stereoscopic views. Under monoscopic viewing conditions the images are acquired by a single camera, otherwise from both.

Fig. 2 A schematic diagram illustrating the 3 x 3 optodes arrangement for the left and right posterior parietal cortex. The locations of the fNIRS emitters (in red), detectors (in blue) and the corresponding channels (numerically labelled) are illustrated. Opted array were centered on P3 (*emitter 13) and P4 (**emitter 18) as in the International 10-20 system.

Fig. 3 (Left) Channels position based on the approximate UI 10/20 positions for left and right posterior parietal cortex optode arrays. (Centre and right) Experimental set-up: the subject sits in front of the da Vinci console, with the fNIRS optodes in his/her head. The fNIRS machine (ETG-4000) and the da Vinci moveable cart are also illustrated.

Fig. 4 (Top) Experiment I: Exemplary platform used as stimulus. (Top-left) Platform as viewed by the subjects. The nearest and farthest spheres are indicated by the circle and the square, respectively. (Top-right) Side view of the same platform for better illustration of the nearest/highest (Circles) and farthest/lowest sphere (Square). (Bottom) Experiment II: platform used as stimulus. (Bottom- left) The pass of the elastic band (purple) between

the robotic graspers. (Bottom-right) The path (arrows) that subjects must follow to put the elastic band on the cones.

Fig. 5 Examples of some actions which were considered as errors, as reported in Table 1, during Experiment II (hand-eye co-ordination). (a) Error N° 2: Moving the robotic grasper to put the elastic band and missing the cone. (b) Error N° 4: Touching the cone while putting or taking the elastic band. (c) Error N° 7: Moving the robotic grasper towards the other robotic grasper to pass the elastic band surpassing or stopping the robotic grasper before reaching the other robotic grasper.

Fig. 6 Experiment I: Object Depth Perception. SPM activation pattern (*t-map*) in both stereoscopic (bottom) and monoscopic (top) visual conditions for HbO₂ and HHb. The channels are reported as an approximation of the UI 10/20 positions for left and right posterior parietal cortex. The figure is best viewed in colors.

Fig. 7 Experiment II: Hand Eye Co-ordination. SPM activation pattern (*t-map*) in both stereoscopic (bottom) and monoscopic (top) visual conditions for HbO₂ and HHb. The channels are reported as an approximation of the UI 10/20 positions for left and right posterior parietal cortex. The figure is best viewed in colors.

Tables

Table 1 Actions which were considered as errors during Experiment II (hand-eye coordination task).

The following actions were considered as errors:	
N° 1	Failing to remove the elastic band from the cone after opening and closing the robotic graspers;
N° 2	Moving the robotic grasper to put the elastic band and missing the cone;
N° 3	Passing over the cone or stopping before reaching the cone;
N° 4	Touching the cone while putting or taking the elastic band;
N° 5	Touching with the robotic grasper the side or the top of the target cone;
N° 6	Opening and closing the robotic grasper without taking the elastic band from the other robotic grasper;
N° 7	Moving the robotic grasper towards the other robotic grasper to pass the elastic band surpassing or stopping the robotic grasper before reaching the other robotic grasper.

Table 2 Comparison of the variable ΔHb (average task Hb – average rest Hb) between subjects across visual conditions and experiments (i.e., hand-eye co-ordination experiment (HEC) on the monoscopic visual condition (2D)). For each channel the *p-value* (Friedman Test) is reported for both changes in HbO₂ and HHb. Significant effects are indicated: * $p < 0.05$, ** $p < 0.001$. The abbreviation HEC refers to the hand-eye co-ordination experiment and ODP to the object depth perception experiment.

Ch.	HbO₂				Ch.	HHb			
	Task-rest (Total mean)					Task-rest (Total mean)			
	HEC 2D	HEC 3D	ODP 2D	ODP 3D		HEC 2D	HEC 3D	ODP 2D	ODP 3D
1	4.958	6.183	2.880	1.760	1	-2.142	-2.154	-2.486	-2.105
2*	1.709	1.708	0.973	2.408	2	-0.647	-2.145	-0.077	0.398
3**	6.799	7.100	3.091	2.465	3	-2.727	-3.482	-1.941	-2.258
4*	7.398	6.145	2.492	3.432	4	-1.127	-1.456	-2.104	-1.870
5	-2.376	-0.346	-1.677	-1.106	5	-0.673	-0.592	-1.070	-1.390
6**	12.263	9.990	3.412	5.058	6	-1.829	-1.401	-2.446	-2.709
7	5.001	2.830	-2.425	-3.022	7	0.370	-0.843	-2.211	-2.856
8**	9.557	10.728	5.180	7.177	8*	-1.603	-0.120	-0.771	-1.491
9*	8.525	6.305	3.559	4.498	9	-1.852	-2.156	-0.562	-0.105
10	2.760	4.982	-1.178	-1.179	10*	0.080	1.052	-0.490	-1.476
11*	10.070	10.301	5.851	7.110	11*	-3.205	-1.640	-1.424	-1.904
12	2.319	0.073	1.602	2.432	12	-2.853	-3.046	-0.138	-0.960
13	7.394	3.905	-0.686	-0.450	13**	0.072	-0.451	-2.463	-2.536
14	6.495	6.908	3.046	4.096	14	-2.122	-2.086	-1.238	-0.704
15*	3.969	3.285	-3.006	-2.559	15**	0.514	1.096	-1.485	-1.464
16*	8.121	6.748	2.498	2.823	16	-0.971	-1.340	-1.607	-1.169
17	9.365	10.488	4.630	5.237	17	-3.327	-2.522	-0.993	-1.009
18*	6.740	5.454	1.606	2.011	18	-0.934	0.288	-1.098	-1.707
19**	7.314	6.984	1.651	2.426	19	-3.019	-2.917	-2.808	-3.632
20	0.747	3.858	1.941	2.327	20**	-3.677	-1.878	0.538	0.376
21	7.040	5.964	4.018	4.926	21**	-3.086	-2.078	-0.916	-1.027
22**	11.247	13.095	4.479	5.368	22*	-0.570	-0.857	-1.489	-2.113
23	1.080	2.944	2.426	1.591	23*	-4.603	-3.542	-0.785	-0.777
24	9.863	9.712	6.227	7.723	24	-3.116	-3.065	-1.932	-1.688

Appendix

Table A1 Post-hoc pair-wise comparison of the variable ΔHbO_2 (average task HbO_2 – average rest HbO_2) for each channel, which has found to be statistically significant by using the Friedman test. The *p-values* (Wilcoxon Sign Rank Test) are reported for each pair-wise comparison. The pair-wise comparisons significantly different (Holm’s sequential Bonferroni correction) are reported in italic on the table. The abbreviation HEC refers to the hand-eye co-ordination experiment and ODP to the object depth perception experiment.

Ch.	HEC_2D VS ODP_2D	HEC_2D VS ODP_3D	HEC_3D VS ODP_2D	HEC_3D VS ODP_3D
2	0.119	0.032	0.849	0.243
3	0.019	<i>0.002</i>	<i>0.007</i>	<i>0.002</i>
4	0.019	0.072	0.04	0.041
6	<i>0</i>	<i>0</i>	<i>0</i>	<i>0.004</i>
8	<i>0.004</i>	0.027	0	0.023
9	<i>0.001</i>	<i>0.002</i>	0.027	<i>0.007</i>
11	0.015	0.018	0.012	0.021
15	<i>0.003</i>	<i>0.014</i>	<i>0.001</i>	<i>0.009</i>
16	<i>0.001</i>	0.011	0.028	0.059
18	<i>0.004</i>	<i>0.01</i>	0.064	0.111
19	<i>0.001</i>	<i>0.008</i>	0.013	0.016
22	<i>0</i>	<i>0.002</i>	<i>0</i>	<i>0.002</i>

Table A2 Post-hoc pair-wise comparison of the variable ΔHHb (average task HHb – average rest HHb) for each channel, which has found to be statistically significant by using the Friedman test. The *p-values* (Wilcoxon Sign Rank Test) are reported for each pair-wise comparison. The pair-wise comparisons significantly different (Holm’s sequential Bonferroni correction) are reported in italic on the table. The abbreviation HEC refers to the hand-eye co-ordination experiment and ODP to the object depth perception experiment.

Ch.	HEC_2D VS ODP_2D	HEC_2D VS ODP_3D	HEC_3D VS ODP_2D	HEC_3D VS ODP_3D
8	0.157	0.781	0.599	0.012
10	0.236	0.141	0.104	0.02
11	0.029	0.071	0.175	0.842
13	<i>0.005</i>	<i>0.003</i>	0.049	0.026
15	<i>0.004</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>
20	<i>0</i>	<i>0</i>	<i>0.01</i>	0.032
21	<i>0</i>	<i>0.002</i>	<i>0.007</i>	0.032
22	0.067	<i>0.002</i>	0.16	<i>0.007</i>
23	<i>0</i>	<i>0.001</i>	<i>0.011</i>	<i>0.017</i>

Table A3 ΔHbO_2 (average task HbO_2 – average rest HbO_2) for each channel and for each experiment and visual condition. The abbreviation HEC refers to the hand-eye coordination experiment and the abbreviation ODP to the object depth perception experiment.

Ch.	HEC_2D	HEC_3D	ODP_2D	ODP_3D
1	4.958	6.183	2.880	1.760
2	1.709	1.708	0.973	2.408
3	6.799	7.100	3.091	2.465
4	7.398	6.145	2.492	3.432
5	-2.376	-0.346	-1.677	-1.106
6	12.263	9.990	3.412	5.058
7	5.001	2.830	-2.425	-3.022
8	9.557	10.728	5.180	7.177
9	8.525	6.305	3.559	4.498
10	2.760	4.982	-1.178	-1.179
11	10.070	10.301	5.851	7.110
12	2.319	0.073	1.602	2.432
13	7.394	3.905	-0.686	-0.450
14	6.495	6.908	3.046	4.096
15	3.969	3.285	-3.006	-2.559
16	8.121	6.748	2.498	2.823
17	9.365	10.488	4.630	5.237
18	6.740	5.454	1.606	2.011
19	7.314	6.984	1.651	2.426
20	0.747	3.858	1.941	2.327
21	7.040	5.964	4.018	4.926
22	11.247	13.095	4.479	5.368
23	1.080	2.944	2.426	1.591
24	9.863	9.712	6.227	7.723

Table A4 Δ HHb (average task HHb – average rest HHb) for each channel and for each experiment and visual condition. The abbreviation HEC refers to the hand-eye coordination experiment and the abbreviation ODP to the object depth perception experiment.

Ch.	HEC_2D	HEC_3D	ODP_2D	ODP_3D
1	-2.142	-2.154	-2.486	-2.105
2	-0.647	-2.145	-0.077	0.398
3	-2.727	-3.482	-1.941	-2.258
4	-1.127	-1.456	-2.104	-1.870
5	-0.673	-0.592	-1.070	-1.390
6	-1.829	-1.401	-2.446	-2.709
7	0.370	-0.843	-2.211	-2.856
8	-1.603	-0.120	-0.771	-1.491
9	-1.852	-2.156	-0.562	-0.105
10	0.080	1.052	-0.490	-1.476
11	-3.205	-1.640	-1.424	-1.904
12	-2.853	-3.046	-0.138	-0.960
13	0.072	-0.451	-2.463	-2.536
14	-2.122	-2.086	-1.238	-0.704
15	0.514	1.096	-1.485	-1.464
16	-0.971	-1.340	-1.607	-1.169
17	-3.327	-2.522	-0.993	-1.009
18	-0.934	0.288	-1.098	-1.707
19	-3.019	-2.917	-2.808	-3.632
20	-3.677	-1.878	0.538	0.376
21	-3.086	-2.078	-0.916	-1.027
22	-0.570	-0.857	-1.489	-2.113
23	-4.603	-3.542	-0.785	-0.777
24	-3.116	-3.065	-1.932	-1.688