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Effects of task complexity and sensory conflict on goal-directed movement

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Abstract

Interactions between brain regions are necessary for compound activities to take place. Accordingly, evaluating hemispheric information processing during skilled behaviour provides valuable knowledge about brain regulation. To this end, the present study assessed the neural changes in response to task complexity and visuomotor discrepancy during motor (drawing) actions. EEG phase synchronization, expressing interregional communication, showed that visuomotor discordance perturbed information processing across both hemispheres, whereas task complexity induced pronounced adjustments in the left (dominant) hemisphere. However, the effects of task complexity and sensorimotor conflict interacted, and suggested that the main process of spatiotemporal integration was localized within the left hemisphere. Furthermore, a significant association between left hemisphere couplings and performance accuracy proposed that connectivity strength and behavioural output are linked with one another. These results suggest that functional connectivity patterns provide higher-order associations for information coding during skilled actions.

Keywords: EEG, functional connectivity, phase synchronization

Daily life activities require skilled movements with various degrees of complexity. In this respect, movement complexity can be expressed in a number of ways, and has previously been associated with factors such as accuracy and speed [10], sequence length [5,20,26], sequence difficulty [6,16], and motor predictability [8]. Overall, complexity covaries with the pattern of brain activation [25], and thus the degree of information processing. Commonly, there is increased activity (effort) for complex as compared to simple movements, and this effect has been strongly associated with the left (dominant) hemisphere, which is also supported from patient work [13,33,36]. The latter denotes hemispheric specialization for motor complexity. Conversely, the right hemisphere is clearly involved in visuo-spatial regulation [11,14,21]. This distinction of lateralized function implies that each hemisphere will contribute in a specific manner to goal-directed activities [30,31]. It further specifies that interregional communication is necessary for aggregate behaviour to take place. Based on the previous, the argument is made that evaluating changes in hemispheric information processing as a function of the task demands will provide valuable knowledge about brain regulation. In particular, it is argued that targeting hemispheric functions will evoke specific neural modifications in order to manage the task requirements.

In the present experiment, motor behaviour with two levels of task complexity was examined in a normal feedback and sensorimotor conflict situation. Here, the hypothesis was made that the experimental manipulations of task complexity and sensorimotor conflict would induce specific information processing in both hemispheres. Moreover, based on lateralization of function, it was hypothesized that task complexity would impact on the left hemisphere, whereas sensorimotor conflict would influence both hemispheres due to disturbed visuoproprioceptive processing and perturbed visuomotor regulation [22]. As an approach to describe brain activity, the data analysis focused on functional connectivity in the frequency domain as determined by EEG techniques. In this respect, the concept of functional connectivity refers to the concurrent activity of brain regions and is usually quantified through patterns of synchronization at different neural sites. It is based on the premise that functional coupling of neural activity provides a means for integrating task-related information. In the context of motor behaviour, EEG functional connectivity

measures have proven to be sensitive indicators for evaluating the dynamics of interregional interactions [e.g., 4,7,15,28], including an association between connectivity strength and behavioural output [3,15,18,29].

Twelve right-handed individuals (age range: 23 ± 6 years, five male) participated in the experiment. To assess handedness, the participants were asked to report on their hand preference, according to the Edinburgh handedness inventory [24]. Based on the individual responses, a handedness quotient was calculated by means of the formula: $[100 \times (\text{Right} - \text{Left}) / (\text{Right} + \text{Left})]$, which ranges between -100 (pure left-handedness) and $+100$ (pure right-handedness). The mean score was 94 ± 5 , thus indicating strong right-handedness. The participants had no history of neurological disease and did not have any artistic experience. In accordance with the declaration of Helsinki, the participants gave informed consent to take part in the study, which was approved by the local ethics committee. The participants were asked to perform drawing movements with their right hand according to two degrees of complexity (Fig. 1). The distinction of complexity was set by the topological nature of the tasks (i.e., number of directional changes at corner points), which determines drawing time [22]. The tasks were executed under 2 conditions; normal vision (control) and mirror-inverted vision, and involved patterns with similar kinematics. Subjects first performed the control conditions followed by the mirror conditions. The order within the control and mirror conditions was counterbalanced. The drawing tasks were performed on a digitizing graphic tablet (Wacom, Intuos3), using an ink- and wireless pen. The pen trajectories were acquired in x- and y-coordinates by using E-Prime software (Psychology Software Tools Inc., Pittsburgh, USA). The templates of the drawings to be performed were placed behind the graphics tablet. In the mirror-reversed condition, a mirror with semi-silvered coated properties was placed between the template and tablet. Subjects were instructed to copy the templates continuously for the duration of the trial starting from a fixed position, as fast and as accurately as possible. Trials lasted 35 s each, and there were 2 trials per task condition. Practice with and without the mirror was provided. There were small breaks in between trials. As an estimate of behavioural performance, path velocity and accuracy (RMS) of the drawings were determined for each task condition.

Insert Fig. 1 about here

Continuous EEG was recorded using the Electrical Geodesics Inc. 128-channel system. EEG signals were amplified, band-pass filtered 0.05 Hz–100 Hz, and sampled at 250 Hz with a vertex reference. Data pre-processing was carried out using BESA software (MEGIS Software GmbH, Gräfelfing, Germany), and epochs contaminated by artifacts such as eye movements and EMG-related activity were corrected for using its algorithm. A reference-free montage was subsequently used for further analysis with the EEGLAB Matlab Toolbox [9]. The trials were segmented into epochs of 800 ms, excluding the first and last epoch, and subjected to a threshold-based rejection of epochs resulting in an average of 138 epochs per subject and task condition. A wavelet analysis extracted time–frequency complex phases using three cycles at frequencies in the low beta band (13–21 Hz), based on earlier work of visuomotor behaviour [7]. A sliding window of 260 ms was used, generating 134 time points with a resolution of 1 Hz. Thereafter, phase synchronization was calculated as an estimate of functional connectivity between brain areas in the frequency domain. It was estimated for all specified time points and frequencies, and subsequently averaged for each subject and task condition. As a measurement of coupling between two signals at any given frequency, phase synchronization varies between 0 (no correlation) and 1 (perfect correlation). To measure indices of cortical activity, a region of interest approach was adopted that focused on a restricted number of electrodes. The electrodes were selected based on earlier EEG studies [7,16,28] and were estimated to overlie prefrontal, premotor, sensorimotor, parietal and occipital areas. The division of electrodes resulted in the following connectivity groupings: intrahemispheric left (F3-FC3, F3-C3, F3-CP3, F3-P3, F3-O1, FC3-C3, FC3-CP3, FC3-P3, FC3-O1, C3-CP3, C3-P3, C3-O1, CP3-P3, CP3-O1, P3-O1), intrahemispheric right (F4-FC4, F4-C4, F4-CP4, F4-P4, F4-O2, FC4-C4, FC4-CP4, FC4-P4, FC4-O2, C4-CP4, C4-P4, C4-O2, CP4-P4, CP4-O2, P4-O2), interhemispheric (F3-F4, FC3-FC4, C3-C4, CP3-CP4, P3-P4, O1-O2). Before statistical operations were conducted, scores were transformed using the inverse hyperbolic tangent to stabilize variances. All the processed data were analyzed using Statistica software (StatSoft Inc., Tulsa, USA). Adjustments were made in case of violation of the sphericity

assumption by using the Greenhouse–Geisser procedure. Post-hoc testing included corrections for multiple comparisons. The analyses involved 2 x 2 ANOVAs on task complexity (easy, complex) and sensorimotor conflict (no mirror, with mirror).

THE EEG phase synchronization data were analyzed separately for intrahemispheric right, intrahemispheric left, and interhemispheric couplings. For *intrahemispheric right connectivity*, the ANOVA showed a significant main effect of sensorimotor conflict [$F(1,11)=6.82$, $p<0.03$, $\eta^2=.22$], which indicated higher coupling in the no mirror than with mirror conditions. The mean scores (\pm SD) were $.348\pm.027$ and $.334\pm.033$ for the no mirror and mirror tasks, respectively. For *intrahemispheric left connectivity*, the ANOVA revealed a significant main effect of sensorimotor conflict [$F(1,11)=4.99$, $p<0.05$, $\eta^2=.29$] and a significant task complexity x sensorimotor conflict interaction [$F(1,11)=17.88$, $p<0.01$, $\eta^2=.11$]. Post-hoc analysis indicated that increased task complexity resulted in higher coupling in the no mirror condition (with normal vision) whereas the opposite effect was noted with mirror-reversed vision ($p<0.05$), (Fig. 2A). This underlines that the left hemisphere couplings became disrupted as task complexity augmented under mirror-reversed vision. Combined the intrahemispheric data suggest a disturbance of the functional balance between both hemispheres when complexity is stringent. This premise is supported from examining the ratio of left vs. right hemisphere activation for the complex task. The ratio, which provides an indication about hemispheric balance, dropped significantly from 1.005 (no mirror) to .977 (with mirror), [$t(11)=2.45$, $p<0.04$]. For *interhemispheric connectivity*, the ANOVA demonstrated a significant main effect of sensorimotor conflict [$F(1,11)=5.89$, $p<0.04$, $\eta^2=.58$], and denoted higher coupling in the no mirror than with mirror conditions. The mean scores (\pm SD) were $.262\pm.026$ and $.253\pm.024$ for the no mirror and mirror tasks, respectively.

The behavioural data were analyzed separately for path velocity and accuracy. For *path velocity*, the ANOVA revealed a significant main effect of task complexity [$F(1,11)=6.29$, $p<0.03$, $\eta^2=.91$], and sensorimotor conflict [$F(1,11)=19.67$, $p<0.01$, $\eta^2=.03$]. The mean scores (\pm coefficient of variation) were $190\pm 9\%$ (no mirror) and $92\pm 17\%$ (with mirror), $150\pm 11\%$ (easy task) and $132\pm 16\%$ (complex task). For *path*

accuracy, the ANOVA showed a significant main effect of task complexity [$F(1,11)=5.56$, $p<0.04$, $\eta^2=.25$] and a significant task complexity x sensorimotor conflict interaction [$F(1,11)=19.34$, $p<0.01$, $\eta^2=.45$]. Post-hoc analyses demonstrated that error increased strongly when the complex as compared to the easy task was performed with mirror-inverted vision ($p<0.05$), (Fig. 2B). A correlation analysis between the left hemisphere couplings and error scores for the complex task in the mirror condition provided a significant correlation ($r=-0.65$, $p<0.05$). This indicates that more errors associated with low intrahemispheric coupling in the dominant hemisphere.

Insert Fig. 2 about here

The brain's functional architecture involves neural processing within segregated areas. Accordingly, the involvement of wide-spread regions is necessary for compound behaviour to occur [30,31]. In the present study, hemispheric information processing was evaluated, using functionally connectivity measures, during motor tasks that involved drawing actions. Previously, it has been established that drawing behaviour engages distributed brain regions [19]; an observation that is supported from patient work that has shown that visuo-spatial tasks are impaired following left as well as right hemisphere lesions [12,36]. However, the intricacy of the drawing activity depends on a number of factors such as feedback availability (normal vs. degraded) and task complexity (characterized by the topology of the figure and spatial characteristics of the components). Both factors will selectively affect the functional activation profiles and influence the quality of visuomotor mapping that is required for successful drawing behaviour. Of note is that different types of drawing activities exist, integrating distinct task constraints and neural regulation [e.g., 23,32]. In the current experiment, the drawing tasks required copying of templates, which implied that the visual model and movement trajectory were in different locations. Therefore, an indirect spatial association between model and trajectory subsisted such that visuomotor transformations from template to drawing space were necessary to perform the assignment skilfully [2]. Relevant in the present context is to distinguish copying from tracing during which the template and trajectory overlap, enabling continuous

visual guidance of the hand in local space [2]. Accordingly, it is argued that the defined demands of the drawing activity will affect the weighting of the sensory signals as well as the adopted strategies (i.e., shifts between model and trajectory), especially in the case of visuomotor incongruence during which the reference frames between the eyes and hand are misaligned [27].

The EEG data revealed that intrahemispheric coupling in the low beta frequency band changed in response to both experimental factors. *First*, visuomotor discordance perturbed information processing within and between hemispheres. It is argued that disturbed visuospatial processing including sensory recalibration occurred in the right hemisphere [17,35], whereas disrupted sensorimotor planning took place in the left hemisphere [22]. Besides changes in intrahemispheric connectivity, the functional transfer between the hemispheres was affected due to visuomotor incongruence, which underlines that interhemispheric interactions are a relevant communication pathway for movement regulation [34].

Second, task complexity impacted on the left (dominant) hemisphere. This finding is in agreement with previous data that have shown that left hemisphere dominance exists for complex actions [13,33]. However, there was also evidence that task complexity and sensorimotor conflict interacted, which is in line with the idea that the main process of spatiotemporal integration occurs within the left hemisphere [1]. That the functional balance between both hemispheres became disturbed due to the combined effect of task complexity and visuomotor discongruence further supports this premise, and suggests that efficient processing and integration between both hemispheric sides is necessary for optimal brain functioning. Furthermore, the significant association between the left hemisphere couplings and performance accuracy provides an indication that connectivity strength and behavioural output are functionally linked with one another. It denotes that a particular magnitude of interregional coupling is necessary to obtain a successful performance. Besides the mutual effect of complexity and conflict on drawing accuracy, it was also shown that both factors reduced drawing speed. In this respect, slowing down of performance is likely due to an increased supervision of the task demands.

Together, the data from the intra- and interhemispheric couplings have provided evidence for context-dependent responses to situations of sensorimotor incongruence and task complexity. The adaptation of functional connectivity profiles, whether decreased or increased, hints at explicit adjustments in view of the task constraints. In particular, reduced synchrony points to disrupted or abnormal interregional communication, whereas increased synchrony reflects tightened or compensatory interactions. Both effects hint at segregation or integration of information processing across brain areas.

In conclusion, daily life activities require complex motor behaviour, and involve various control processes that engage distributed brain regions. In case of intricate situations, optimal information processing can be disturbed and lead to deteriorated performance. In the present study, it was shown that visuomotor incongruence and task complexity modulated interregional communication in a distinctive manner. Accordingly, the data suggest that interactions between brain areas provide higher-order information coding in view of skilled behaviour.

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Figure Caption

Fig. 1. The templates used in the experiment, which included two versions of an easy task (left-sided panels) and complex task (right-sided panels).

Fig. 2. Intrahemispheric connectivity of the left hemisphere (A) and drawing error (B) as a function of task complexity (easy vs. complex) and sensorimotor conflict (no mirror condition with normal vision vs. mirror condition with mirror-inverted vision). The means \pm SE are illustrated.

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Fig. 1

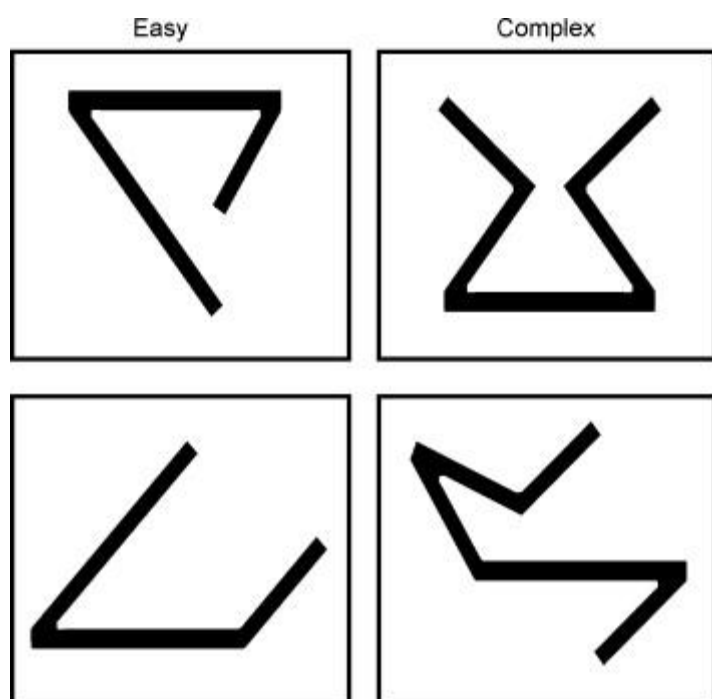


Fig. 2

