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Competing interests statement

The author declares no competing financial interests.

FURTHER INFORMATION

Blue Gene: <http://www.research.ibm.com/bluegene>
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was one of the first to make explicit that each side is responsible for specialized functions by contrasting the importance of the anterior lobe of the left hemisphere with that of the posterior lobe of the right hemisphere. These ideas laid the foundation for a dominant theme in the laterality literature that arose in the twentieth century and continues to the present day: namely, that the left hemisphere has a dominant role in linguistic abilities whereas the right hemisphere is responsible for visuospatial functions².

Whereas Hughlings Jackson and other early neurologists stressed the contralateral organization of the human motor system, Hugo Liepmann (1863–1925) highlighted a marked asymmetry between the hemispheres in terms of skilled action. Specifically, Liepmann³ argued that the left hemisphere has a dominant role in the control of movement, postulating that this hemisphere contains ‘movement formulae’ that are intended for both sides of the body. These ideas were dramatically reinforced by initial reports of patients who underwent the callosotomy procedure for the treatment of intractable epilepsy⁴. In particular, these patients experience difficulty producing voluntary movements with the left hand in the early months after surgery, which suggests that such control requires transcallosal input from the left hemisphere.

Today, the prevalent view in the neurosciences is that specialized functions of the left hemisphere are essential for skilled movement and language. This lateralization profile is quite well established for right-handers^{5,6}, and might be set early in development^{7,8} after the emergence of key motor and perceptual specializations in initial gestation^{9,10}. Indeed, most researchers assume that the left hemisphere specialization for movement- and language-associated functions are related to one another^{5,6} (but see REF. 11 for an alternative view). However, the basis of these asymmetries has engendered considerable debate¹². One dominant hypothesis emphasizes functional connections between the cortical hand motor area and language circuit^{13–15} that may have been essential for the evolution of language from manual gestures rather than vocal calls¹⁶, which is supported by the robust use of gestures that typically accompany speech¹⁷. Accordingly, Broca’s area has been observed to be associated with various non-language motor functions such as planning, recognition and imitation of actions^{18–20} as well as with syntactic operations required for the hierarchical representation of sequential behaviours²¹.

OPINION

Dynamics of hemispheric specialization and integration in the context of motor control

Deborah J. Serrien, Richard B. Ivry and Stephan P. Swinnen

Abstract | Behavioural and neurophysiological evidence convincingly establish that the left hemisphere is dominant for motor skills that are carried out with either hand or those that require bimanual coordination. As well as this prioritization, we argue that specialized functions of the right hemisphere are also indispensable for the realization of goal-directed behaviour. As such, lateralization of motor function is a dynamic and multifaceted process that emerges across different timescales and is contingent on task- and performer-related determinants.

Owing to advances in neuroimaging techniques coupled with clinical work, considerable progress has been made in understanding the functional rules of brain organization. Two fundamental principles have been proposed: functional specialization, which refers to the idea that particular neural regions perform specialized computations; and functional integration, which implies that specific tasks require extensive interactions between specialized neural regions¹. It is mainly the premise of functional specialization that has received the lion’s share of attention in the neurosciences, as supported by evidence in favour of anatomical segregation. Conversely, the assessment of functional integration has proved to be more challenging and usually

benefits from statistical methods used to infer dependencies in neural activity. These two principles must be considered as complementary when considering cortical function¹.

Taking a broad view, the localizationist doctrine has led to the identification of functional specializations associated with the two cerebral hemispheres. Building on the seminal ideas of Franz Gall (1758–1828), Paul Broca (1824–1880) and Carl Wernicke (1848–1905) presented evidence that certain language abilities are impaired following damage to specific regions in the left hemisphere (Broca’s and Wernicke’s areas in the left inferior frontal gyrus, and the left superior and middle temporal gyri, respectively). John Hughlings Jackson (1835–1911)

Box 1 | **Handedness**

Handedness refers to the well-defined preference whereby one hand is used in favour of the other in a consistent manner. It is a fundamental behavioural characteristic that becomes stabilized during development¹⁰⁶, and can be evaluated in terms of preference (the hand that is chosen to carry out a task) or performance (the hand that is more proficient at a task), although both expressions are closely related. Handedness is often measured by comparing the relative performance of both hands on a given task such as peg moving¹⁰⁷, finger tapping¹⁰⁸ or reaching⁵⁰. About 90% of humans are more skilled with the right than left hand, although the degree of manual asymmetry varies as a function of age¹⁰⁹ and task complexity¹¹⁰. Handedness is not only evident during unimanual tasks but is also present during bimanual movements¹¹¹. Although the two hands cooperate in achieving a common goal, such as unscrewing a lid from a jar, each is consistently assigned a particular task. In general, the dominant hand takes on the manipulative role while the non-dominant hand serves a postural role. Manual dominance persists when performing bimanual tasks for which the limbs assume a similar function, such as bilateral circle drawing during which the preferred hand leads the non-preferred hand¹¹².

The aim of this article is to present the viewpoint that lateralization of motor function is a dynamic process. Although we contend that in right-handers the left hemisphere takes on a dominant role for the regulation of motor behaviour, we also discuss evidence that supports the specialized functions of the right hemisphere for motor control. Accordingly, we propose that lateralization of motor function is a versatile process during which the functional involvement of both hemispheres is not fixed but is flexible and driven by several fundamental factors.

The left hemisphere

With respect to motor behaviour in humans, the issue of hemispheric specialization is closely tied to handedness (BOX 1) and therefore linked to asymmetric brain function. Left hemisphere dominance for skilled movement has been attributed to anatomical and functional asymmetries of the primary motor cortex (M1) and descending pathways^{22,23} as well as to secondary motor and association areas²⁴. An extensive motor map contralateral to the preferred hand supports an asymmetry of M1 in right-handers^{22,25} and probably corresponds to experience-dependent changes that begin early in development²⁶. FIGURE 1 shows an example of M1 maps in a right-handed subject when carrying out various tasks with the preferred and non-preferred hand. As illustrated, the different actions identified as spatially segregated dipolar sources are more dispersed in the left than in the right hemisphere²³. An experiential component to this asymmetry is consistent with the fact that there is considerable plasticity of M1 maps following pathological or traumatic changes, as well as during motor learning and consolidation^{27,28}. The more extensive connectivity of the left M1 with associated corticospinal

tracts is further supported by new MRI techniques that correlate functional and anatomical information using functional MRI (fMRI) and diffusion tensor imaging²⁹. Furthermore, on the basis of transcranial magnetic stimulation data, it has been suggested that excitability of the corticospinal system of right-handers is higher in the left than in the right hemisphere³⁰.

The asymmetry of secondary motor and association areas, which probably reflects a consequence of specialized regions implementing distinct functions, is particularly evident from clinical work. Patients with left hemisphere lesions, especially of parietal areas, are likely to show impairments in producing skilled actions with either hand, whereas comparable right hemisphere lesions produce deficits that are

largely restricted to the contralateral hand³¹. Further evidence for hemispheric asymmetry of association areas is provided by neuroimaging work in healthy participants. FIGURE 2a shows the greater involvement of the left compared with the right premotor and parietal areas in higher-order aspects of action that are related to movement complexity³². Overall, the literature underscores the involvement of the left hemisphere in movement organization and selection^{33,34} (FIG. 2b) as well as in motor imagery and learning^{35,36}. Various hypotheses have been offered as a functional basis for this asymmetrical pattern, including a role in sequential behaviour³², bimanual coordination^{37,38}, tool use³⁹, evaluation of the body state⁴⁰ and interpretation of perceived actions⁴¹. Furthermore, a left hemisphere specialization for temporal processing, at least for sequential movements⁴², has been proposed, which fits with its role in spoken language as well as sign language⁴³.

The right hemisphere

The role of the right hemisphere in motor organization is less well defined. With respect to M1, there is evidence for a reduced representation in the right compared with the left hemisphere in right-handers, which relates to decreased dexterity of the less-preferred hand⁴⁴. Regarding association areas, functional specializations related to higher-order planning do not seem to be strongly developed, although spatial response

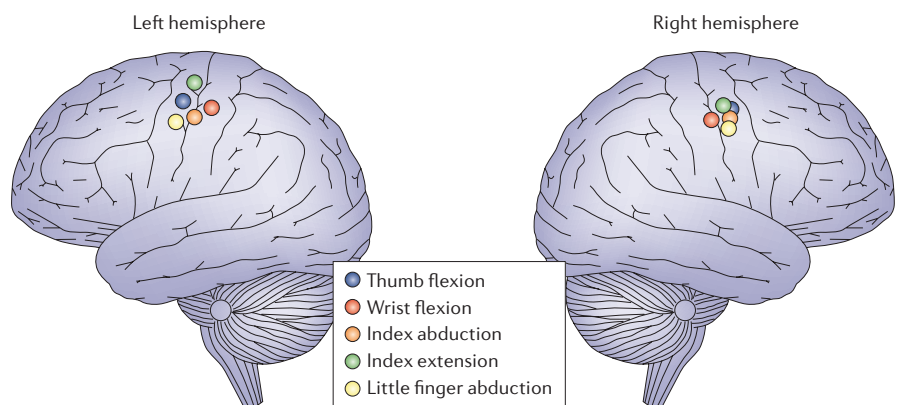
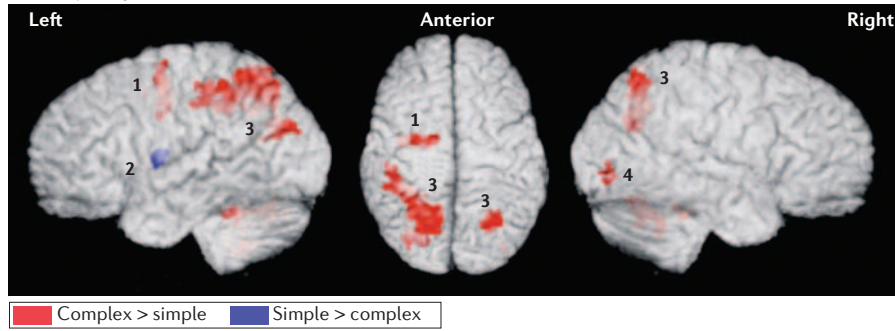


Figure 1 | Hand motor representation. Current dipole sources of motor activity for different hand and finger movements during magnetoencephalography recordings superimposed onto MRI reconstructions in a right-handed subject. All dipole sources were localized within the hand area of the primary motor cortex. Spatial arrangement of neural sources for hand and digit movements was non-somatotopic and covered a larger area in the left than the right hemisphere. Motor performance parameters as obtained from surface electromyographic analysis did not differ significantly between the preferred and non-preferred limb²³. Modified, with permission, from REF. 23 © (1998) American Physiological Society. Anatomical image adapted, with permission, from REF. 119 © (1996) Appleton & Lange.

a Complexity of movement



b Motor attention

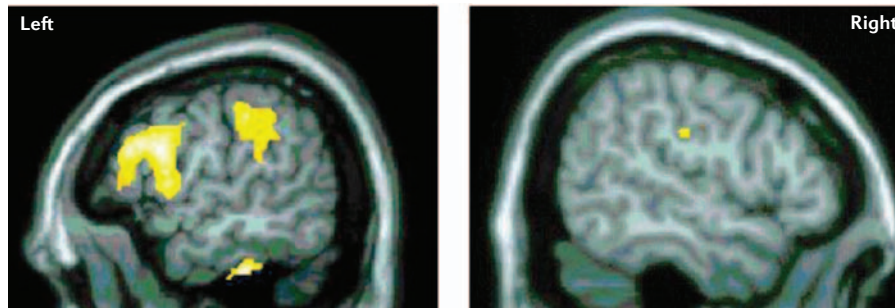


Figure 2 | Left hemisphere dominance. a | Neural activation pattern showing regions with significant differences in MRI signal intensity for subtractions of simple versus complex sequences. Participants carried out experimental conditions that consisted of key presses in response to numeric sequences presented on a screen. The simple condition required repetition of a single key press whereas the complex condition consisted of a heterogeneous sequence that always included three fingers and four transitions. The areas that were most strongly activated for the complex movements were in the left hemisphere, regardless of which hand performed the task, and included the dorsal premotor (1), insula (2), superior parietal (3) and extrastriate (4) cortices³². **b** | Shows relative regional cerebral blood flow increase and extent associated with motor attention. Participants performed finger responses and covertly attended or did not attend to the movements before execution. Despite only left-hand responses being produced, the attention-related activity was almost exclusively in the left hemisphere. The left parietal cortex was prominently involved, with activations in the anterior part of the supramarginal gyrus and the anterior intraparietal sulcus. Additional activation foci were observed in lateral premotor and prefrontal regions, including the pars opercularis of Broca's area, and in the cingulate sulcus³⁴. Panel **a** reproduced, with permission, from REF. 32 © (2004) MIT Press. Panel **b** reproduced, with permission, from REF. 34 © (2001) MIT Press.

selection has been linked with the right hemisphere⁴⁵. This restricted involvement might be due to the right hemisphere requiring strong external cues to select a particular motor representation from various options⁴⁶ or to a selection mechanism that involves mainly exploratory processing of novel situations⁴⁷.

The latter argument concerning novel situations would be in line with a theory of hemispheric control that assumes that the left hemisphere controls open-loop aspects of the movement (based on well-established motor programmes), whereas the right hemisphere is crucial for closed-loop aspects of the movement (dependent on sensory feedback)⁴⁸. However, recent research in patients does not support this clear dichotomy of hemispheric asymmetry.

Instead, this work suggests that the separation of different components of reaching movements on the basis of open- and closed-loop processing is relative rather than absolute⁴⁹. Alternatively, it has been proposed that the left hemisphere controls limb trajectory whereas the right hemisphere regulates limb position and posture⁵⁰. This premise is in agreement with patient data⁵¹ that show differential effects of left and right hemispheric lesions on the initial and final phases of aiming movements. At present, both hypotheses are considered to be convergent: open-loop left hemisphere specialization is limited to feedforward specification of task dynamics, whereas closed-loop right hemisphere specialization includes sensory-mediated mechanisms that control final limb position⁵².

Nonetheless, various lines of evidence convincingly support a dominant role for the right hemisphere in various spatial functions, such as spatial memory, learning and orienting^{53–56}. It has been suggested that this right-sided dominance is due to preferential encoding of global features in contrast to the specialization of the left hemisphere for processing local features^{57,58}. Computationally, this distinction possibly results from the differential sensitivity of the hemispheres to spatial frequency information: amplification of low spatial frequencies underscores information at the global level whereas intensification of high spatial frequencies highlights information at the local level^{57,58}. Alternatively, a right hemisphere specialization for spatial functions might relate to its involvement in the control of spatial attention for both the left and right visual fields^{59,60}, or a monitoring function that especially becomes apparent in conflict situations⁶¹, as when experiencing a mismatch between motor intention, proprioception and/or visual feedback⁶² (FIG. 3).

Task- and performer-related influences

The previous sections summarized various hypotheses concerning how the cerebral hemispheres provide differential contributions to the control of skilled actions. As outlined, some functions are lateralized to one hemisphere or the other, which might be beneficial in terms of reducing conduction delays⁶³ or downgrading interference from incompatible processes⁶⁴. Here, we propose that the relative involvement of each hemisphere in motor behaviour depends on task- and performer-related characteristics. This implies that several factors dynamically shape the contribution of each hemisphere: on the one hand, this involves the type and complexity of the movement; on the other hand, the skill level, CNS status and attentional focus of the performer will also influence the manner in which the two hemispheres contribute to the control of movement.

Task-related characteristics. Movement type-related processing evidently has an important role in the mechanisms of control of skilled actions. In particular, sequential representations and their resources are associated with the left hemisphere, independent of the performing hand³². In view of this, the left hemisphere may be especially involved in the planning of sequential acts that implicate notable response selection, preparation and/or retrieval^{32,33,65}. For goal-directed reaching, each hemisphere is proposed to

contribute in a distinct manner to controlling the specification of the trajectory and final position⁵⁰. The distinction is due to the left hemisphere's contribution in the planning of the limb dynamics whereas the right hemisphere is essential for specifying the final position of the reaching movement through sensory regulation.

The contribution of each hemisphere is also modulated by movement complexity. Whereas a simple movement such as unimanual finger tapping is organized by a local neural circuit, more complex actions such as those involving a sequence of finger movements engage distributed (often bilateral) networks^{32,65}. In this respect, recruitment of both hemispheres might be affected by augmented attentional or executive control requirements, or by the use of operations that are specialized in each hemisphere. It is assumed that interhemispheric pathways allow for relevant coupling or decoupling of information^{66,67}. That input is indeed communicated between both hemispheres is evident, for example, from motor transfer studies, which address intermanual information transmission when a specific task is practised with one hand. In general, performance benefits are found to occur in the trained as well as the untrained hand⁶⁸.

Performer-related characteristics. Goldberg *et al.*⁶⁹ proposed that right hemisphere processing is driven by the external environment, whereas left hemisphere processing is guided by internal representations (see also REF. 48; see REF. 49 for an alternative outcome). This line of thinking is consistent with observations from patients with spatial neglect, following right parietal injury, who show a severe shift of exploratory movements towards the right side that becomes markedly attenuated when goal-directed movements are performed⁷⁰. It suggests that both types of action necessitate differential input or supporting processes, with a distinctive contribution from both hemispheres. These functional differences between the two sides would suggest a right-to-left shift of hemispheric importance as expertise develops. Indeed, skill development is often associated with a partial transition from externally to internally generated movement control. For example, when learning to accomplish a difficult bimanual task⁷¹, activation in the right hemisphere decreases over time, whereas left hemisphere activation becomes more prominent. The former might be due to a reduced requirement for monitoring spatial features of the movements, whereas the latter probably

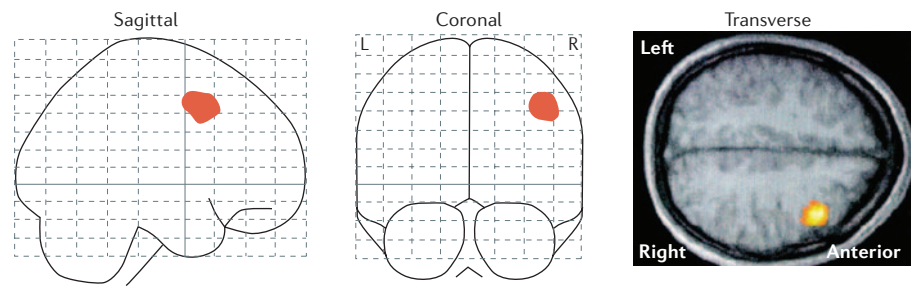


Figure 3 | Right hemisphere dominance. Relative regional cerebral blood flow increase and extent related to conflicting visual feedback when producing Luria's bimanual coordination task, which involves anti-phase versus in-phase movements. A mirror was used to manipulate visual feedback from the left hand by showing a reflection of the right hand (that is, virtual left hand). Participants were instructed to look towards their left hand (real or virtual). The main effect of the mirror was an increase in activity in the right dorsolateral prefrontal cortex and right superior posterior parietal cortex (not shown). Focal activation in the right dorsolateral prefrontal cortex was associated with the interaction term of non-veridical/veridical visual feedback on anti-phase/in-phase movements, suggesting a specific monitoring role of this area for motor intentions in conflict situations when spatial task demands are emphasized⁶². Reproduced, with permission, from REF. 62 © (1999) Oxford University Press.

relates to an augmented involvement of a consolidated representation⁷² (FIG. 4).

The CNS status of the performer is linked to a change in operational strategy due to the particular neural circumstances. For example, after injury, cortical regions associated with bilateral control such as premotor cortex may take on enhanced motor processing responsibilities, and as such have a crucial role in recovery of function⁷³. This implies that both hemispheres are endowed with functional capabilities that can be exploited under specific conditions, and supports the idea that neural involvement for task production is malleable. Although there is evidence that motor deficits differ after left versus right hemisphere damage^{31,48,51}, this issue requires further detailed evaluation, with particular consideration of the site and extent of neural damage as well as task constraints and handedness.

Finally, attention can modulate the involvement of the two hemispheres⁷⁴. In particular, hemispheric biases may change as spatial attentiveness shifts between global and local levels of representation that rely on right and left hemisphere processes, respectively⁵⁸, or between motor and non-motor demands of self-produced actions⁷⁵ for which directed motor attention enhances selection of the representation.

The findings described above show that the task demands and the characteristics of the performer have powerful effects on the processing requirements for movement control and may bias hemispheric asymmetries and interhemispheric interactions. It illustrates that a dynamic balance between the existing constraints induces

certain operational modes. For example, whereas global spatial guidance, especially relevant for novel and unexplored actions, is associated with the right hemisphere, representational processing that occurs on the basis of experience-based planning is more effectively mediated by the left hemisphere. This implies that the functional contribution of both hemispheres is flexibly driven. It is this flexibility that underlies skilled and adaptive motor behaviour. In this respect, the examination of motor tasks such as tapping and finger sequencing, which are often used in experimental designs, might have biased research outcomes in favour of distinct (primarily left hemisphere) processing requirements. Accordingly, future work should focus on a wider range of tasks with different degrees of motor complexity to delineate the proficiency of each hemisphere in movement control.

Information gating and integration

If certain functions are lateralized to one hemisphere or the other, then efficient gating of information is essential for movements that draw on these functions. Many of these interactions occur via the corpus callosum, allowing for the transfer of (pre)motor, feedback, error and attention-related input^{76,77}. This communication between the hemispheres involves functional inhibition as well as facilitation. Inhibitory interactions are thought to be crucial during the preparation of unilateral actions to counteract the production of default mirror movements⁷⁸ — that is, involuntary movements of one hand that accompany the voluntary actions of the other hand. From a lateralization

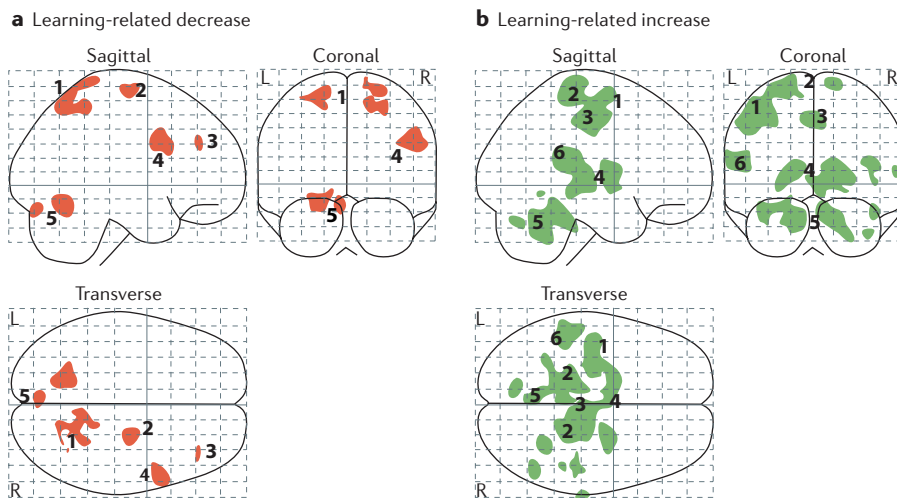


Figure 4 | Learning-related changes. **a** | Neural activation pattern of learning-related decreases (pre>post) during the acquisition of a bimanual coordination task that required a complex spatiotemporal relationship between the limbs — that is, cyclical flexion–extension movements of both hands with a phase offset of 90° (REF. 72). Decreases in activation with learning were predominantly observed in the right hemisphere and included the superior parietal cortex (1), right dorsal premotor cortex (2), right dorsolateral prefrontal cortex (3), right ventral premotor cortex (4) and left cerebellar lobule VI (5). **b** | Neural activation pattern of learning-related increases (post>pre) during acquisition of the same bimanual task⁷². Brain areas that showed an increase in activation with learning were principally located in the left hemisphere, comprising the left dorsal premotor cortex (1), or were more bilateral — that is, primary motor cortex (2), cingulate motor cortex (3), putamen/globus pallidus (4), cerebellum dentate nuclei (5) and superior temporal gyrus (6). Reproduced, with permission, from REF. 72 © (2004) Elsevier Science.

viewpoint, there is evidence to suggest that in right-handers inhibitory effects between both motor cortices are greater from the left to the right hemisphere than vice versa⁷⁹. This type of functional distinction could contribute to hemispheric differences in motor control and probably emerges in early childhood, during which certain inhibitory processes in the hemispheres assume an asymmetrical developmental course⁸⁰.

Facilitation of information transfer between the hemispheres is essential when their respective processing is required for successful task performance. In the context of movement control, the corpus callosum and its mechanism of information gating has especially been of interest with respect to bimanual coordination tasks. This work has revealed that the degree of interhemispheric communication relates to task complexity⁸¹ and is required for learning new movement patterns^{82–85}. Therefore, callosal interactions provide a high-level link for the specification of movement parameters (such as amplitude) or response selection^{86,87} and probably constitute a physiological basis for neural crosstalk^{88,89} that becomes evident when people carry out bimanual tasks with dissimilar movement characteristics^{61,90}. In summary, adaptive motor behaviour relies

on inhibitory processes that may help to exploit the processing benefits associated with hemispheric specialization as well as on facilitatory processes that allow for the integration of information across both hemispheres. This implies that the allocation of processing resources for motor behaviour is a dynamic process for which segregation and integration of function flexibly coexist.

The question then emerges of how the brain manages to incorporate information from specialized but distributed regions, each of which may process inputs in a unique manner. To understand this, it is important to consider how information processing is coordinated within and between hemispheres. A possible mechanism for such large-scale inter-regional interactions is the temporary creation of dynamic connections that rely on the synchronization of neural activity^{91–93}. In human and animal studies, the measurement of coherence has found relevant application in various neurophysiological data such as electroencephalography, magnetoencephalography and local field potential recordings^{38,94,95} (BOX 2). In particular, coherence provides a means to capture neural communication across brain sites⁹⁶, for which effective information coding can be related to different

frequency bands. For example, synchronized activity in movement-related brain areas that has been most readily associated with motor function is in the beta frequency range (~14–30 Hz)^{38,81,83,85}. Accordingly, the dynamic organization of neural activity in the frequency domain may provide a means for uniting information processing in view of the task demands: the close association between changes in cortico-cortical coherence and behavioural performance lends support to this proposal^{97–99}. This dynamic organization also hints that the harmonized activity from widespread brain areas represents a basic mode of information communication across different frequencies, which underlies the formation of neural networks of which the processing outcome is translated into proficient behaviour. On the basis of the previous discussion, we suggest that with skill development, motor representations that become established in the left hemisphere may support efficient inter-regional information processing. For example, during acquisition of a new bimanual assignment, it has been shown that an initial profile of cortico-cortical couplings is gradually adjusted as the routine becomes settled and behavioural performance is optimized^{183,85}, which eventually results in a functional pattern that is primarily orchestrated by the left hemisphere when carrying out well-learned bimanual tasks³⁸.

A dynamic view of motor lateralization

The previous sections have shown that the functional participation of both hemispheres in motor regulation is not fixed but is dynamic and versatile. Here we present a viewpoint that captures this dynamic disposition and argue that lateralization of motor function is characterized by hemispheric and interhemispheric dynamics across different timescales. The hemispheric dynamics support major movement-related functions such as motor attention, temporal processing and spatial (global, local) attention, which are distributed across both hemispheres. Only through a compliant information exchange, delineated as interhemispheric dynamics, can optimal motor behaviour be attained. Projections between the hemispheres, mainly via the corpus callosum, allow for interactive functioning. It is believed that hemispheric asymmetries and an optimal balance between the hemispheres is vital as both developmental diseases and pathology — for example, autism and schizophrenia — have been linked, in part, to atypical modulations such as an inconsistent hemispheric specialization, or

Box 2 | Coherence

Coherence represents a measurement of linear covariation between two signals in the frequency domain. It is mathematically bounded between zero and one, whereby one signifies a perfect linear association and zero denotes that the signals are not linearly related at that particular frequency. The premise is that when activities from spatially remote events covary they tend to interact, also denoted as functional connectivity. Standard coherence as a measure of functional coupling provides a link between two signals but no directional information. To this end, estimators can be constructed, such as a directed transfer function, which examines asymmetries in inter-regional information flow and establishes a direction of drive between the coupled sites^{38,113}. As a large-scale approach to study motor control functioning and mechanisms, the application of coherence and associated measures provides a valuable analytical tool to investigate functional connectivity between neural sites and changes that occur due to various factors such as task complexity, context and learning^{81,83,98,114}. It also allows the determination of anomalous as well as compensatory connectivity patterns in pathological conditions^{115–118}.

a dysfunctional integration among neural systems^{100,101}. A timescale dynamic drives the (inter)hemispheric regulation and operates on various levels: first, a short-term basis, which is influenced by factors such as attention and context; second, a medium-term basis, which is affected by elements such as learning and recovery of function; and third, a long-term basis, which is moulded by development, ageing, high-level expertise and chronic disease. Here, we have focused on factors that constitute the short- and medium-term basis, but all levels interact with and influence each other. For example, the acquisition of a new task (medium term) will be contingent on the developmental stage of the learner (long term). This viewpoint contrasts with a traditional perspective that treats lateralization of motor function as a static process.

Conclusions

A principal phenomenon of human brain regulation is lateralization of function⁴¹. Traditionally, emphasis has been on left hemisphere supremacy for language and motor control versus right hemisphere dominance for spatial representation and attention. Although specialized areas are probably predetermined, it is through the combination of inter-regional interactions that coherent behaviour is achieved^{102–104}. In this respect, we have proposed that the strength of functional connectivity patterns parallels an increased reliance on left hemisphere representations, which accordingly support a refined motor repertoire. Apart from this prioritization, we argue that specializations of the right hemisphere also contribute uniquely to skilled behaviour. Moreover, it is through an active interplay of neural processing, mainly via callosal projections, that the transfer of information for sensorimotor integration, intention, decision making and response preparation¹⁰⁵

is supported. This processing is not static but is dynamically driven by task- and performer-related determinants across various timescales, which together shape the overall motor behaviour. Therefore, the pattern of hemispheric asymmetry that underlies movement organization is multifaceted and more complex than a simple dichotomy of function.

Until recently, our understanding of the brain areas involved in the organization of skilled actions was almost exclusively provided by studies of patients with brain injuries, in whom deficits in performance were associated with the site of pathology. This literature emphasized that left and right hemisphere injury can selectively disrupt specific cognitive–motor functions, and has yielded important insights into how the brain represents and regulates motor behaviour. These findings have been confirmed, updated and extended by functional imaging studies. Although this research further underscores that specific functions are preferentially implemented by one hemisphere or the other, it also suggests that there is a more complex organization that involves a distributed engagement of multiple neural regions for successful task performance. Therefore, a crucial problem for future research is to explore the relative contribution of the hemispheres' regions across various timescales and task demands. It is particularly the study of these dynamics that requires further effort, because it offers a window into the nature of (inter)hemispheric processing. This will also promote the unique but too often neglected processing capabilities of the right hemisphere in movement regulation. These insights are not only decisive for theories of motor control in health and disease but also for advancing rehabilitative interventions to improve motor disability due to neural damage.

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Competing interests statement

The authors declare no competing financial interests.

CORRIGENDA

Gene therapy: can neural stem cells deliver?

Franz-Josef Müller, Evan Y. Snyder and Jeanne F. Loring

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On page 77, under the subheading 'Angiogenesis', the fourth sentence should read "Angiogenesis resulting from brain pathology could enhance neural stem cell mobilization by producing chemoattractants such as VEGF."

Monitoring of stored and available fuel by the CNS: implications for obesity

Randy J. Seeley and Stephen C. Woods

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On page 904, under the subheading 'The CNS melanocortin system', the ninth sentence should read "POMC-expressing neurons are found largely in the arcuate nucleus, and leptin^{58–60} and insulin¹¹⁰ both decrease POMC gene expression there."

Reference 110. Benoit, S.C. *et al.* The catabolic action of insulin in the brain is mediated by melanocortins. *J. Neurosci.* **22**, 9048–9052 (2002).