Motor and Visuospatial Attention and Motor Planning After Stroke: Considerations for the Rehabilitation of Standing Balance and Gait

Sue Peters, Todd C. Handy, Bimal Lakhani, Lara A. Boyd, S. Jayne Garland

Attention and planning can be altered by stroke, which can influence motor performance. Although the influence of these factors on recovery from stroke has been explored for the upper extremity (UE), their impact on balance and gait are unknown. This perspective article presents evidence that altered motor and visuospatial attention influence motor planning of voluntary goal-directed movements poststroke, potentially affecting balance and gait. Additionally, specific strategies for rehabilitation of balance and gait poststroke in the presence of these factors are discussed. Visuospatial attention selects relevant sensory information and supports the preparation of responses to this information. Motor attentional impairments may produce difficulty with selecting appropriate motor feedback, potentially contributing to falls. An original theoretical model is presented for a network of brain regions supporting motor and visuospatial attention, as well as motor planning of voluntary movements. Stroke may influence this functional network both locally and distally, interfering with input or output of the anatomical or functional regions involved and affecting voluntary movements. Although there is limited research directly examining leg function, evidence suggests alterations in motor and visuospatial attention influence motor planning and have a direct impact on performance of gait and balance. This model warrants testing comparing healthy adults with individuals with stroke.

S. Peters, MPT, Department of Physical Therapy, The University of British Columbia, Vancouver, British Columbia, Canada.

T.C. Handy, PhD, Department of Psychology, The University of British Columbia.

B. Lakhani, PhD, Department of Physical Therapy, The University of British Columbia.

L.A. Boyd, PhD, Department of Physical Therapy, The University of British Columbia.

S.J. Garland, PhD, Department of Physical Therapy, The University of British Columbia, 212-2177 Wesbrook Mall, Vancouver, British Columbia V6T 1Z3, Canada. Address all correspondence to Dr Garland at: jayne.garland@ubc.ca.

[Peters S, Handy TC, Lakhani B, et al. Motor and visuospatial attention and motor planning after stroke: considerations for the rehabilitation of standing balance and gait. *Phys Ther*. 2015;95: 1423–1432.]

Published Ahead of Print: April 30, 2015
Accepted: April 19, 2015
Submitted: October 31, 2014

After stroke, many people experience sensorimotor impairments that disrupt motor performance of balance and gait.[1] Most of the movements executed in a given day are voluntary and goal directed, requiring the capacity to plan movements according to those goals. Also, the ability to attend to certain relevant stimuli while ignoring others is needed for living in the community. Paying attention and planning movements are vital to many community-dwelling adults poststroke, as they are known to have difficulty performing another task while walking.[2] Thus, the importance of understanding the mechanisms underlying attention and planning is paramount to poststroke recovery and integration into functional community living.

Operational Definitions

Motor planning is defined as the integration of sensory afferent information[3] with known internal representations of body anthropometrics (eg, leg length, joint range of motion, muscle force)[4] based on previous experience, integrated with a movement goal[5] for the purpose of generating an upcoming movement. For example, if the goal is to stand up and start walking, motor planning combines the visuospatial information about the environment with somatosensory feedback of current leg and trunk position and past experiences of walking—all prior to the onset of movement. The functions of motor planning are: (1) to prepare for an upcoming voluntary action and (2) to maintain a state of readiness or preparedness for possible unplanned perturbations to the current movement goal.

Motor attention is defined as the ability to selectively process somatosensory input relevant to the movement goal.[6] It can prime the motor plan with relevant somatosensory feedback while disregarding irrelevant information. These types of attentional functions require integration among several brain areas and are subserved by various networks.[7,8] In the previous example, where an individual is preparing to stand up and walk, motor attention can modulate sensory afferent information that is being processed during motor planning. The feedback related to where the leg is in space is directed toward motor planning regions, whereas auditory information may not reach the motor planning regions if it is not deemed important to the motor plan.

Visuospatial attention selects the relevant visual and spatial input in the environment to be accounted for in the motor plan. This type of attention ensures the motor plan contains pertinent visuospatial information. Clinical examinations of attentional processes often consider the influence of visuospatial neglect on motor output and have been reviewed extensively in the literature.[9,10] However, with or without neglect, difficulties with motor planning and attention may be present after stroke. Consequently, this review will not directly examine neglect but rather focuses on the integration of visuospatial attention into motor planning.

Clinical Relevance of Attention After Stroke

Functional motor recovery after stroke is influenced by the attentional system. For example, one study showed that the ability to be attentive, as measured by clinical attention tests administered 2 months poststroke, significantly correlated with motor and functional outcomes 2 years later.[11] A prospective observational study in older adults identified those who fell as having poor attention and increased postural sway when standing with eyes closed.[12] After a stroke, individuals are more than twice as likely to fall compared with healthy controls.[13] Therefore, it is possible that altered motor attention may be a factor in falls incidence poststroke. Although the role of motor attention has been studied poststroke using dual-tasking paradigms,[14] the link between lower extremity (LE) motor performance and motor attention or visuospatial attention has yet to be examined in the stroke population.

Clinical Importance of Motor Planning After Stroke

Of equal importance to motor attention is considering how motor planning influences motor performance. Most of the evidence for motor planning after stroke has been obtained from UE movements. Deficits in motor performance of the UE are related, in part, to poor motor planning.[15] Taking more time to plan a movement poststroke also is associated with altered motor performance, such as reduced precision and coordination of the UE after stroke,[16,17] and the time required to plan a UE movement after stroke has been shown to decrease with rehabilitation.[17] Certain physical therapy treatments, such as constraint-induced movement therapy, improve motor planning of the hand[18] and increase cortical blood flow in motor planning areas,[19] which may indicate active cortical reorganization with rehabilitation. Considering the often-cited goals of improving standing balance and gait and reducing falls after stroke, it is essential that we begin to consider the impact of altered motor planning on LE movements. To date, there is limited research to inform scientists or clinicians about the role of motor planning in the performance of functional movements made by the LE after a stroke.

In the LE, past work assumed the reciprocal action of walking was primarily driven through central pattern generators in the spinal cord,[20] which may explain the lack of neurophysiological studies of motor planning and visuospatial cortical networks relating to gait. However, there is evidence to suggest that there is cortical involvement in step initiation,[21] LE motor planning,[22] and motor attention. Studies of motor attention and planning in the UE can inform how motor performance in the LE may be influenced by motor attention and planning.[23,24] Other potential subcortical regions influencing motor performance in the LE include the vestibular system and the basal ganglia, and their contributions to motor control have been reviewed elsewhere.[25–27] Although the central nervous system affords significant flexibility and some overlapping functions, anatomical evidence suggests that certain brain regions may be linked to movement of specific body parts.[28] As neuroanatomical specificity likely plays a role in functional motor performance, it is important to determine the differences and similarities in the brain activity for motor attention in UE and LE voluntary movement planning.

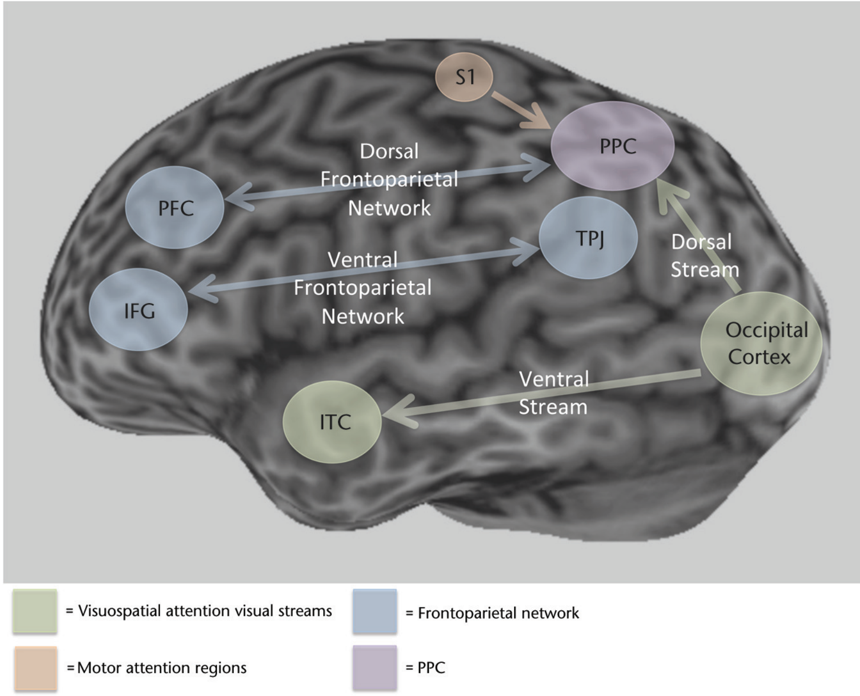

Figure 1.
The dorsal and ventral streams include the occipital cortex and the posterior parietal cortex (PPC) and inferior temporal cortex (ITC), respectively. The dorsal frontoparietal network includes the PPC and the prefrontal cortex (PFC). The ventral frontoparietal network includes the inferior frontal gyrus (IFG) and the temporoparietal junction (TPJ). Motor attention includes the primary sensory cortex (S1) and the PPC. The PPC is important for the dorsal visual stream (part of visuospatial attention), the dorsal frontoparietal network, and motor attention.

This perspective article has 3 main objectives: (1) to propose a theoretical model for an anatomical and functional network of cortical brain regions that supports motor and visuospatial attention and motor planning of voluntary goal-directed movements, (2) to discuss how stroke may affect this network and lead to altered LE function and poor balance and gait, and (3) to suggest considerations for rehabilitation of standing balance and gait after stroke.

Visuospatial Attention and Its Influence on Motor Planning

Visuospatial attention selects relevant sensory information and supports the preparation of responses to this information. The part of the environment that an individual is attending to can modulate the planning of a goal-directed movement. The Premotor Theory of Attention has been influential in understanding the relationship between motor planning and visuospatial attention.[29] It postulates that: (1) motor planning and visuospatial attention use the same neural circuitry, (2) planning a movement directs visuospatial attention toward the upcoming movement goal, and (3) the ocular system is specialized to orient visuospatial attention to the movement being prepared. As a result, attention is drawn to the sensory and motor feedback related to the upcoming motor goal.

There are 2 different visual pathways in the cortex that are affected by visuospatial attention—the dorsal and ventral streams, which are anatomically consistent with the superior and inferior longitudinal fasciculi (Fig. 1). The ventral stream functions to enable visual object recognition, and the dorsal stream is important for visually guided action directed toward an object.[30] The ventral stream, which includes the occipital cortex and the inferior temporal cortex, processes visual input regarding the color, size, and shape of an object or the environment.[31,32] If a lesion is present in the ventral stream, difficulty with object recognition, or visual agnosia, can occur[33] (Table). Visual agnosia after a stroke can include difficulty with recognizing faces, words, or common

Table.
Summary of Anatomical and Functional Regions Associated With Motor and Visuospatial Attention and Motor Planning

Anatomical/Functional Region	Known Function	Potential Functional Effects After a Lesion
Dorsal stream	Visually guided action directed toward an object	Apraxia
Ventral stream	Object recognition	Visual agnosia
Dorsal frontoparietal network	Selects relevant sensory information and prepares responses to this information	Difficulty sifting visuospatial information to identify cues for the motor plan
Ventral frontoparietal network	Identifies relevant stimuli and interrupts dorsal system if an important event occurs	May have difficulty changing from one motor goal to another
Motor attention (posterior parietal cortex)	Orienting a limb in space based on attentional priorities	Limited prediction of where limb will be in space, reduced movement sequencing
Supplementary motor area	Self-initiated movement planning	Increased cognitive effort and slower motor planning of self-initiated movements
Premotor cortex	Externally cued movement planning	Increased cognitive effort and slower motor planning of externally cued movements

objects.[34] The dorsal stream, comprising the occipital cortex together with the posterior parietal cortex (PPC), carries information about the position and nature of goal-oriented objects or the environment as it relates to actions that can be performed.[35] Lesions of the dorsal stream may produce apraxia,[36] where difficulty with imitation of an action (ie, difficulty following gestured commands from a physical therapist) may occur. Importantly, the functional separation of the 2 visual streams allows for partial preservation of visuospatial processing after a lesion in one of them.[37] However, interaction between the dorsal and ventral streams may be required for purposeful actions,[38] such as reaching and grasping or standing up to walk in a complex environment.

Other brain regions also are involved in visuospatial attention and have overlapping functions with motor planning. For example, when a graspable "tool-like" object such as a coffee cup enters the visual field, increased brain activity is observed in the supplementary motor area (SMA),[39] inferior parietal lobule, and the premotor cortex (PMc), indicating that motor planning can be tied to visuospatial attention for an object.[39,40] To date, nearly all research in this field has focused on reaching and grasping, yet it is likely that the functional demands of posture and gait when interacting with objects or the environment require similar patterns of brain network activity. However, it remains unclear whether visuospatial attention affecting stroke also affects LE movement planning.

Visuospatial Attention After a Stroke

A stroke may alter visuospatial attention. However, one study demonstrated that despite a lesion that may directly alter visuospatial attention, cues in the environment can influence subsequent motor planning and performance.[41] That is, although a stroke in the right parietal cortex resulted in a reduction in visuospatial attention toward the left visual field, this reduction was attenuated when cup handles were presented, allowing for a left-hand grasp, suggesting that the visual system may be correctly and unconsciously extracting action-related information for grasping and then modulating attention by activating the specific motor plan the object represents.[41] This finding is encouraging for clinicians working with individuals who have difficulty with visuospatial attention, as object-related cues to direct attention may be useful during therapy. During rehabilitation, LE-specific objects, such as a patient's own shoes or socks, may direct visuospatial attention to the object location. Also, gait retraining may be more effective in the patient's own home or community, if visuospatial attention is impaired. Currently, it is unknown whether visuospatial attention also can be attenuated by LE-specific environmental cues, yet it is very likely that safe and independent mobility requires intact visuospatial attentional processing.

Frontoparietal networks in the brain also are involved with visuospatial attention by generating attention to the spatial features of a planned movement.[42] Visuospatial attention can be voluntarily alerted to a location in space with attentional shifts producing activity in the dorsal frontoparietal attention network[43] (Fig. 1). This dorsal network, comprising the prefrontal cortex (PFC) and the PPC, is engaged when prioritized shifts of attention in space are related to movement goals[44] (Table). Similar to the dorsal stream, the dorsal frontoparietal network functions for goal-directed selection of relevant sensory information and for preparation of responses to this information. A physical therapist may engage the dorsal frontoparietal network by verbally directing the patient's attention to the movement goal. For example, if the goal of therapy is to increase gait distance, the physical therapist may draw the patient's attention to a destination (eg, "walk to the kitchen").

In contrast, the ventral frontoparietal network—inferior frontal gyrus and temporoparietal junction—identifies relevant stimuli and interrupts the dorsal system when an important or salient event occurs, such as encountering an obstacle during gait[45] (Fig. 1). If the movement goal were to stand up and walk across the room, the dorsal frontoparietal network would identify the relevant visual and spatial sensory cues prior to movement, such as current position or angle of hips and knees relative to feet, in addition to the position of environmental obstacles needed to walk around to get to the destination. This dorsal frontoparietal network helps to prepare a response by outputting the selected relevant visuospatial information downstream to motor planning regions. The ventral frontoparietal system serves to interrupt activity in the dorsal system in the event of an unexpected sensory event or perturbation to standing balance, which likely allows for a quick balance correction.[46] The cortical networks required to process incoming sensory stimuli likely utilize the dorsal and ventral frontoparietal attentional network, together with the dorsal and ventral streams[47] (Fig. 1). If a stroke affects the dorsal frontoparietal attention system, it may be difficult to sift through incoming visuospatial sensory information to identify relevant cues for the motor plan[48] (Table). If the ventral frontoparietal system is lesioned, unexpected perturbations to gait may not interrupt the current motor plan, potentially resulting in slower balance corrections to the perturbation.

Based on the aforementioned evidence, rehabilitation of standing balance and gait for people with visuospatial attention deficits may be more effective in an environment containing only the items needed for the task. For example, if the treatment goal is to improve skilled walking by walking on multiple surfaces (eg, from concrete to carpet), clearing the environment of all items except for those needed for the task, may facilitate task-relevant visuospatial attention. Progression to real-world situations may include gradually adding more visual stimuli as visuospatial attention improves. If the ventral frontoparietal network is damaged, difficulty with changing from one motor goal to another may occur, possibly influencing the ability to step quickly in response to a perturbation while walking and increasing the chance for a fall. In rehabilitation, the therapist may engage the ventral frontoparietal network by providing obstacles during gait in a safe and controlled gait training environment, such as body-weight–supported treadmill training.[49] During walking, the physical therapist might place obstacles on the treadmill at unexpected intervals and ask the patient to step over them as quickly as possible while practicing interrupting gait.

Motor Attention and Its Influence on Motor Planning

Motor attention is the selection of relevant somatosensory input for a movement goal, and it primes the motor plan with relevant somatosensory feedback while disregarding irrelevant information.[50] Visuospatial attention and motor attention are thought to be similar, with attentional processes selecting relevant visuospatial or somatosensory information for the motor plan.[6] According to Cohen and Andersen, a goal-directed behavior (eg, voluntary movement to interact with objects or the environment) can be considered "a dynamic link between a sensory stimulus and a motor act."[51(p553)] This dynamic link requires the intermediary steps of altering visuospatial and motor attention toward salient stimuli, including the transformation of external space to internal coordinates,[51] to form an appropriate motor plan. Motor attention and visuospatial attention converge with this "coordinate transformation." The environment is encoded in the brain in several egocentric reference frames.[52] A coffee cup placed on a table can have a variety of reference frames (ie, relative to one's eyes, relative to one's arm, relative to the table), and performing these frame-of-reference calculations is important for completing a motor task successfully, calculating the difference between the current limb position and the desired limb position to complete the goal.[51]

These calculations are possible because the central nervous system has internal representations for constants, such as UE and LE length, and knowledge that production of force at certain joint angles will put the body part in a known space (based on experience), and these internal representations and knowledge can be identified prior to movement and incorporated into a motor plan.[4] These internal representations and previous knowledge allow for prediction of where a hand or foot will be in space prior to movement onset. Impaired visuospatial attention may produce difficulty with encoding the space around us, whereas motor attentional impairments may produce difficulty with selecting the appropriate feedback for this current-to-desired limb calculation. Many of these calculations are performed in the PPC—a part of both the dorsal frontoparietal and the motor attention networks[53] (Fig. 1). Sensory signals converge on the PPC from many different sensory modalities, including the primary sensory cortex (S1), where the combined signals allow for altering the sensory gain (up or down), depending on the attentional priorities given to the sensory signals,[54] allowing the PPC to encode these variables in the output to motor planning regions[51] (Fig. 1). For example, if the movement goal is to stand on a moving bus, sensory signals from the visual, vestibular, and somatosensory systems converge on the PPC, where sensory information relevant to the goal of standing on a moving surface may take priority over somatosensation from the arm and hand. The PPC sends the prioritized sensory information to motor planning areas.

More broadly, the parietal cortex is known to be involved with motor attention, as evidenced by: (1) neuroimaging studies of healthy adults demonstrating parietal activity during movement preparation[55] and (2) lesions in the left parietal lobe affecting the ability to disengage attention from one planned movement to another.[23,56] The supramarginal gyrus (SMG), part of the parietal cortex, functions for orienting a limb in space and is connected with S1[57] and the PMc and SMA cortices.[58] Additionally, motor attention activity is present in the left SMG and the anterior intraparietal sulcus—both left parietal regions, even with left-hand responses.[55] The dominant role for the left parietal cortex, specifically the SMG, for disengaging motor attention can explain why some individuals after stroke with left but not right parietal lesions find movement sequencing difficult even with the ipsilesional hand. Adults with lesions in the left hemisphere have difficulty disengaging motor attention from a planned movement to another, suggesting the left parietal cortex has a role in motor attention.[23] In summary, the role of the parietal cortex, in particular the left hemisphere, for motor attention during motor planning is for orienting a limb in space, for altering planned movements, and for movement sequencing. If the PPC is damaged after a stroke, failing to perform the appropriate coordinate transformations and movement sequences will likely influence the motor plan and subsequent motor performance (Table). As a result, reduced visuospatial and motor attention could increase the incidence of falls.

Dual Tasking as a Means to Assess Motor Attention

Studies of motor attention in the LE conventionally examine dual tasking, the most common being a cognitive task performed during standing or walking, although dual motor tasks also have been examined. The types of combined tasks, whether directing attention to a motor task or a cognitive task, likely produce differing cortical demands. The use of dual-tasking paradigms to study attention is based on the following assumptions: (1) that the capacity for information processing is restricted; (2) that each task performed requires a finite capacity for information processing; and (3) if the 2 tasks are performed together, requiring more than the total capacity, performance on one or both tasks decreases.[59] However, if the performance of both tasks decreases, the exact attentional cost is difficult to determine.[59] When healthy young adults are standing still on a force platform during a dual cognitive/motor task, they demonstrate increased body sway relative to single-task performance, which suggests prioritization of the attentionally demanding cognitive task over the motor attention for postural control as evidenced by the decreased performance on the motor task.[60] In contrast, when older adults perform a dual cognitive/motor task, they tend to prioritize postural control of the motor task with compensatory motor strategies.[61] Maintaining postural control through compensation during dual tasks may indicate that older adults who use this strategy have reduced adaptability to perturbations of standing balance.[62] A possible outcome of this type of compensatory pattern may be the need to resort to a stepping strategy to avoid a fall if perturbed.[59]

Beyond standing, motor attention has been studied during dual tasks, including stepping and gait. Altered performance during dual tasking, such as the inability to talk while walking, is significantly associated with increased fall risk among older adults.[63] Safe ambulation requires attention, even in healthy adults, and dual-task costs generally increase with pathology.[64] The risk of falls may be exacerbated by basic motor impairments, a decline in the ability to divide attention to perform dual tasks, and altered executive function.[64] Following a stroke, altered gait parameters (eg, decreased stride length and gait speed) during dual tasking suggest that motor attention for gait remains a high priority after stroke.[65–67] Additionally, individuals after stroke demonstrate diminished cognitive function while performing a dual cognitive/motor task, which may indicate that common daily tasks such as obstacle crossing while walking require disproportionate attention and prioritization of the motor task over the cognitive task.[68] In addition to gait and stepping performance, altered motor attention during dual-task performance after stroke was seen when participants were instructed to stand as symmetrically as possible while force platforms assessed the contribution of each LE to weight-bearing symmetry.[69] During the cognitive task, weight-bearing asymmetry increased, suggesting that symmetric weight bearing is attention demanding.

During rehabilitation, a physical therapist may improve motor attention by using a dual-task training paradigm increasing postural task demands as motor performance improves, perhaps starting with the patient in a symmetrical weight-bearing position. Therapy after a lesion in the left parietal cortex may require the therapist to specifically train LE movement sequences. For example, if the patient requires retraining of transferring from the bed to a chair, rehabilitation may be more effective if the pattern of movements remains the same even if the bed or chair surfaces or heights change. Motor attention selects relevant somatosensory information required for the motor goal, and the motor plan accounts for this factor.

Motor Planning After Stroke

After stroke, brain activity in regions associated with motor planning is often altered. Motor planning is known to involve activity in the SMA, PMc, and subcortical structures, such as the basal ganglia and cerebellum.[70] Motor planning deficits identified for UE movements after stroke include altered regional brain activity, such as the loss of ipsilesional activity during motor planning of paretic UE movements.[16] In other studies, nonparetic hand flexion produced activity in the contralateral primary motor cortex (M1) similar to healthy adults, whereas paretic hand flexion activated S1 bilaterally,[71] in addition to increased SMA activity.[72] This finding suggests that more cortical resources are demanded for motor planning of tasks in the paretic hand. Using electroencephalographic analysis, a longer planning duration was associated with increased time taken to plan a movement,[73] another reflection of a higher cognitive demand during planning.[73,74] However, it is unknown whether slower motor planning is a beneficial or harmful compensatory mechanism.

In typical day-to-day gait and balancing tasks, taking more time to plan a movement may be a positive protective feature of the poststroke motor planning network to prevent errors. After a stroke, increased time in planning a route that navigates around obstacles is likely to be safer than being inadequately prepared. Alternatively, an individual may experience harmful effects from a prolonged planning duration, such as slow adjustments for obstacles during gait, which may result in a fall. Regardless of the consequence, compensation through altered network activity likely occurs to allow for motor planning after a stroke.

Type of Movement Cue Influences Activity of Cortical Regions

Motor planning regions produce different activity depending on the type of movement cue given. The SMA is considered essential for movements produced without external stimuli (ie, self-initiated movements), and the PMc is engaged in selecting movements based on external stimuli (ie, externally cued movements), such as a "go" cue.[72–75] During an externally cued movement, a person responds to a signal without prior knowledge of the precise timing of signal presentation. Using functional magnetic resonance imaging (fMRI) during hand movements in healthy adults, self-initiated movement produced higher basal ganglia activity, together with an earlier response in the SMA, while both self-initiated and externally cued movements had similar activity in the contralateral M1 just before movement onset.[76] This finding is supported by other fMRI studies demonstrating that brain activity in the SMA, sensorimotor cortices, and deeper brain structures reflects the demands of self-initiated movement preparation not present in externally cued conditions.[74,77–79] Because these studies suggest that motor planning requires a coordinated network of brain activity in multiple regions, it is conceivable that motor planning may be negatively influenced by stroke.

Rehabilitation of motor planning for the LE after a stroke should consider the type of cueing provided, as well as the amount of cortical effort required. Although the majority of goal-directed movements are self-initiated, if a lesion is present in the SMA, therapy may be more successful if external cues are provided (Table). Rehabilitation can use external cues with the therapist indicating when and how to move, essentially providing a "go" cue. On the other hand, if the SMA is spared, self-initiated movement may take advantage of the increased amount of brain activity and increased subcortical activity observed experimentally. Tailoring rehabilitation to the lesion location found on admission computed tomography or magnetic resonance imaging may be useful in the provision of therapy (Table).

Proposed Theoretical Model for Brain Regions Supporting Motor and Visuospatial Attention and Motor Planning of Voluntary Goal-Directed Movements

A proposed network including anatomical and functional regions known to be involved with visuospatial and motor attention and how these attentional processes influence motor planning is demonstrated in Figure 2. The PFC selects a movement-related goal while sensory signals from the dorsal visual stream and S1 converge on the PPC. While the ventral stream identifies what an object is, the dorsal stream provides location and spatial orienta-

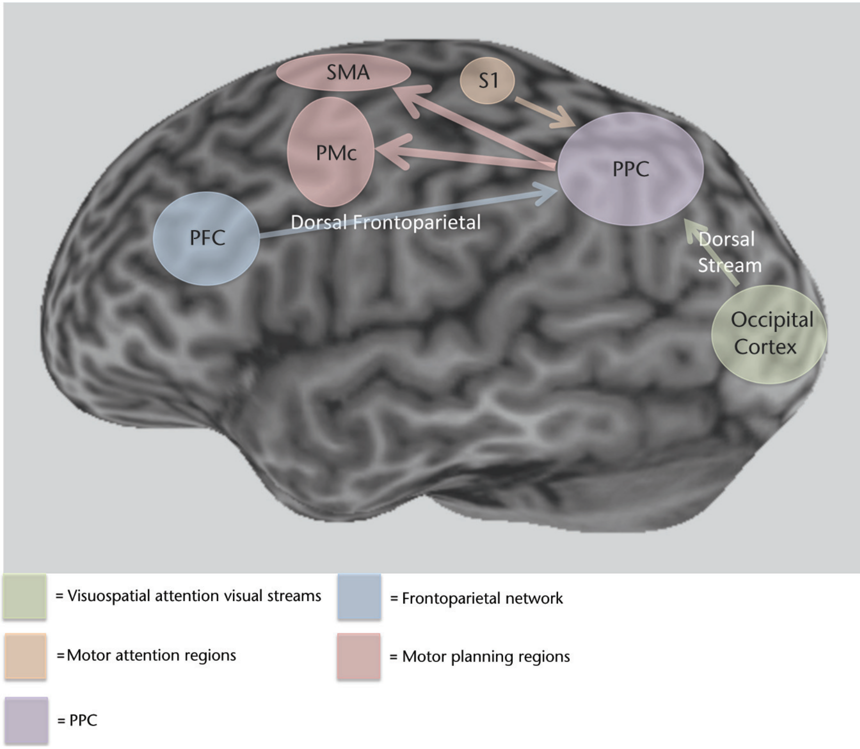

Figure 2.
The prefrontal cortex (PFC) selects a movement-related goal while sensory signals from the dorsal stream and primary sensory cortex (S1) converge on the posterior parietal cortex (PPC). The PPC narrows (or converges) the attentionally selected signals pertaining to the goal, based on visuospatial and motor attentional priorities. The supplementary motor area (SMA) and premotor cortex (PMc) areas receive this information and generate a motor plan based on the attention-filtered sensory signals and movement goals. The PPC is important for the dorsal visual stream (part of visuospatial attention), the dorsal frontoparietal network, and motor attention.

tion of those objects. Therefore, the dorsal stream is considered to be integral to the model, as an object can be determined to be an obstacle to the movement-related goal without identifying what the object is, although in extreme circumstances, such as navigating through a dangerous environment, both streams are required for safety. The PPC narrows (or converges) the attentionally selected signals pertaining to the goal based on visuospatial and motor attentional priorities. The SMA and PMc areas receive this information and generate a motor plan based on the attention-filtered sensory signals and movement goals.

Stroke may affect this functional network both locally and distally by interfering with input or output of the anatomical or functional regions involved. Functional performance can be affected as a result. This model requires testing comparing healthy controls with individuals who have sustained a stroke, and with paretic and nonparetic UE and LE motor planning, as it is the first rehabilitation-focused theoretical model integrating motor and visuospatial attention with motor planning. It is unknown whether lesions affecting visuospatial or motor attention produce compensatory activity, or which regions might participate in compensation, if it occurs. It is also unknown whether the motor planning functions of the SMA and PMc could be interchangeable if a lesion is present in one motor planning region.

Conclusions

Although there is limited research directly examining motor and visuospatial attention and motor planning in the LE, strokes in different brain regions could alter visuospatial and motor attention and motor planning, which would affect motor performance during gait and standing. The likely brain networks important for LE motor and visuospatial attention and motor planning involve the dorsal and ventral visual streams for visuospatial processing, the dorsal and ventral frontoparietal network for visuospatial and motor attention, and the premotor regions (SMA and PMc) for motor planning. Future studies are needed to link brain activity involved in attention and motor planning with clinical measures of motor performance in the LE. Additionally, lesion location may influence the functions of visuospatial and motor attention and planning such that health care professionals involved in rehabilitation after stroke may benefit from detailed lesion descriptions based on computed tomography or magnetic resonance imaging. The extent to which motor planning and attentional deficits limit the remediation of motor function of balance and gait after a stroke is still unknown.

This perspective article highlights the need of future research aimed at determining how motor and visuospatial attention and motor planning interact to produce voluntary, goal-directed LE movements such as gait after a stroke. This type of research would allow health care professionals involved in poststroke care to better understand how these different types of impairments affect motor function and to better tailor therapeutic interventions. Future research should attempt to identify which current and novel rehabilitation treatments improve planning and attention for standing balance and gait using the model developed in this perspective article.

All authors provided concept/idea/research design and consultation (including review of manuscript before submission). Ms Peters provided writing.

DOI: 10.2522/ptj.20140492

References

1 Duncan PW, Goldstein LB, Matchar D, et al. Measurement of motor recovery after stroke: outcome assessment and sample size requirements. *Stroke.* 1992;23:1084–1089.

2 Takatori K, Okada Y, Shomoto K, et al. Effect of a cognitive task during obstacle crossing in hemiparetic stroke patients. *Physiother Theory Pract.* 2012;28:292–298.

3 Ghez C, Favilla M, Ghilardi MF, et al. Discrete and continuous planning of hand movements and isometric force trajectories. *Exp Brain Res.* 1997;115:217–233.

4 Butler J, Lebowitz H. Part VI: movement. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 4th ed. New York, NY: McGraw-Hill Companies Inc; 2000:653–872.

5 Zimmermann M, Meulenbroek RG, de Lange FP. Motor planning is facilitated by adopting an action's goal posture: an fMRI study. *Cereb Cortex.* 2012;22:122–131.

6 Goldberg ME, Segraves MA. Visuospatial and motor attention in the monkey. *Neuropsychologia.* 1987;25:107–118.

7 Posner MI, Petersen SE. The attention system of the human brain. *Annu Rev Neurosci.* 1990;13:25–42.

8 Fan J, Posner M. Human attentional networks. *Psychiatr Prax.* 2004;31(suppl 2):S210–S214.

9 Proto D, Pella RD, Hill BD, Gouvier WD. Assessment and rehabilitation of acquired visuospatial and proprioceptive deficits associated with visuospatial neglect. *NeuroRehabilitation.* 2009;24:145–157.

10 Pierce SR, Buxbaum LJ. Treatments of unilateral neglect: a review. *Arch Phys Med Rehabil.* 2002;83:256–268.

11 Robertson IH, Ridgeway V, Greenfield E, Parr A. Motor recovery after stroke depends on intact sustained attention: a 2-year follow-up study. *Neuropsychology.* 1997;11:290–295.

12 Whitney J, Close JC, Jackson SH, Lord SR. Understanding risk of falls in people with cognitive impairment living in residential care. *J Am Med Dir Assoc.* 2012;13:535–540.

13 Jorgensen L, Engstad T, Jacobsen BK. Higher incidence of falls in long-term stroke survivors than in population controls: depressive symptoms predict falls after stroke. *Stroke.* 2002;33:542–547.

14 Brown LA, Sleik RJ, Winder TR. Attentional demands for static postural control after stroke. *Arch Phys Med Rehabil.* 2002;83:1732–1735.

15 Dean PJ, Seiss E, Sterr A. Motor planning in chronic upper-limb hemiparesis: evidence from movement-related potentials. *PLoS One.* 2012;7:e44558.

16 Colebatch JG. Bereitschaftspotential and movement-related potentials: origin, significance, and application in disorders of human movement. *Mov Disord.* 2007;22:601–610.

17 Daly JJ, Fang Y, Perepezko EM, et al. Prolonged cognitive planning time, elevated cognitive effort, and relationship to coordination and motor control following stroke. *IEEE Trans Neural Syst Rehabil Eng.* 2006;14:168–171.

18 Tan C, Tretriluxana J, Pitsch E, et al. Anticipatory planning of functional reach-to-grasp: a pilot study. *Neurorehabil Neural Repair.* 2012;26:957–967.

19 Kononen M, Kuikka JT, Husso-Saastamoinen M, et al. Increased perfusion in motor areas after constraint-induced movement therapy in chronic stroke: a single-photon emission computerized tomography study. *J Cereb Blood Flow Metab.* 2005;25:1668–1674.

20 Zehr EP, Duysens J. Regulation of arm and leg movement during human locomotion. *Neuroscientist.* 2004;10:347–361.

21 Koenraadt KL, Roelofsen EG, Duysens J, Keijsers NL. Cortical control of normal gait and precision stepping: an fNIRS study. *Neuroimage.* 2014;85 Pt 1:415–422.

22 Yazawa S, Shibasaki H, Ikeda A, et al. Cortical mechanism underlying externally cued gait initiation studied by contingent negative variation. *Electroencephalogr Clin Neurophysiol.* 1997;105:390–399.

23 Rushworth MF, Nixon PD, Renowden S, et al. The left parietal cortex and motor attention. *Neuropsychologia.* 1997;35:1261–1273.

24 Kelso JA, Fuchs A, Lancaster R, et al. Dynamic cortical activity in the human brain reveals motor equivalence. *Nature.* 1998;392:814–818.

25 Hitier M, Besnard S, Smith PF. Vestibular pathways involved in cognition. *Front Integr Neurosci.* 2014;8:59.

26 Stiles L, Smith PF. The vestibular-basal ganglia connection: balancing motor control. *Brain Res.* 2015;1597:180–188.

27 Cullen KE. The vestibular system: multimodal integration and encoding of self-motion for motor control. *Trends Neurosci.* 2012;35:185–196.

28 Schieber MH. Constraints on somatotopic organization in the primary motor cortex. *J Neurophysiol.* 2001;86:2125–2143.

29 Smith DT, Schenk T. The premotor theory of attention: time to move on? *Neuropsychologia.* 2012;50:1104–1114.

30 Almeida J, Mahon BZ, Zapater-Raberov V, et al. Grasping with the eyes: the role of elongation in visual recognition of manipulable objects. *Cogn Affect Behav Neurosci.* 2014;14:319–335.

31 Goodale MA, Milner AD. Separate visual pathways for perception and action. *Trends Neurosci.* 1992;15:20–25.

32 Goodale MA, Milner AD, Jakobson LS, Carey DP. A neurological dissociation between perceiving objects and grasping them. *Nature.* 1991;349:154–156.

33 De Renzi E. Disorders of visual recognition. *Semin Neurol.* 2000;20:479–485.

34 Martinaud O, Pouliquen D, Gerardin E, et al. Visual agnosia and posterior cerebral artery infarcts: an anatomical-clinical study. *PLoS One.* 2012;7:e30433.

35 Goodale MA. How (and why) the visual control of action differs from visual perception. *Proc Biol Sci.* 2014;281:20140337.

36 Dawson AM, Buxbaum LJ, Duff SV. The impact of left hemisphere stroke on force control with familiar and novel objects: neuroanatomic substrates and relationship to apraxia. *Brain Res.* 2010;1317:124–136.

37 Cloutman LL. Interaction between dorsal and ventral processing streams: where, when and how? *Brain Lang.* 2013;127:251–263.

38 Goodale MA, Kroliczak G, Westwood DA. Dual routes to action: contributions of the dorsal and ventral streams to adaptive behavior. *Prog Brain Res.* 2005;149:269–283.

39 Handy TC, Schaich Borg J, Turk DJ, et al. Placing a tool in the spotlight: spatial attention modulates visuomotor responses in cortex. *Neuroimage.* 2005;26:266–276.

40 Handy TC, Grafton ST, Shroff NM, et al. Graspable objects grab attention when the potential for action is recognized. *Nat Neurosci.* 2003;6:421–427.

41 di Pellegrino G, Rafal R, Tipper SP. Implicitly evoked actions modulate visual selection: evidence from parietal extinction. *Curr Biol.* 2005;15:1469–1472.

42 Peelen MV, Mruczek RE. Sources of spatial and feature-based attention in the human brain. *J Neurosci.* 2008;28:9328–9329.

43 Kincade JM, Abrams RA, Astafiev SV, et al. An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. *J Neurosci.* 2005;25:4593–4604.

44 Ptak R. The frontoparietal attention network of the human brain: action, saliency, and a priority map of the environment. *Neuroscientist.* 2012;18:502–515.

45 Greene CM, Soto D. Functional connectivity between ventral and dorsal frontoparietal networks underlies stimulus-driven and working memory-driven sources of visual distraction. *Neuroimage.* 2014;84:290–298.

46 Ghafouri M, McIlroy WE, Maki BE. Initiation of rapid reach-and-grasp balance reactions: is a pre-formed visuospatial map used in controlling the initial arm trajectory? *Exp Brain Res.* 2004;155:532–536.

47 Chica AB, Bartolomeo P, Lupianez J. Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behav Brain Res.* 2013;237:107–123.

48 Ptak R, Schnider A. The dorsal attention network mediates orienting toward behaviorally relevant stimuli in spatial neglect. *J Neurosci.* 2010;30:12557–12565.

49 DePaul VG, Wishart LR, Richardson J, et al. Varied overground walking training versus body-weight–supported treadmill training in adults within 1 year of stroke: a randomized controlled trial. *Neurorehabil Neural Repair.* 2015;29:329–340.

50 Greenberg AS, Gmeindl L. Strategic control of attention to objects and locations. *J Neurosci.* 2008;28:564–565.

51 Cohen YE, Andersen RA. A common reference frame for movement plans in the posterior parietal cortex. *Nat Rev Neurosci.* 2002;3:553–562.

52 Colby CL, Goldberg ME. Space and attention in parietal cortex. *Annu Rev Neurosci.* 1999;22:319–349.

53 Szczepanski SM, Pinsk MA, Douglas MM, et al. Functional and structural architecture of the human dorsal frontoparietal attention network. *Proc Natl Acad Sci USA.* 2013;110:15806–15811.

54 Kam JW, Dao E, Farley J, et al. Slow fluctuations in attentional control of sensory cortex. *J Cogn Neurosci.* 2011;23:460–470.

55 Rushworth MF, Krams M, Passingham RE. The attentional role of the left parietal cortex: the distinct lateralization and localization of motor attention in the human brain. *J Cogn Neurosci.* 2001;13:698–710.

56 Rushworth MF, Johansen-Berg H, Gobel SM, Devlin JT. The left parietal and premotor cortices: motor attention and selection. *Neuroimage.* 2003;20(suppl 1):S89–S100.

57 Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey, I: parcellation of areas based on distinctive limbic and sensory corticocortical connections. *J Comp Neurol.* 1989;287:393–421.

58 Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey, II: evidence for segregated corticocortical networks linking sensory and limbic areas with the frontal lobe. *J Comp Neurol.* 1989;287:422–445.

59 Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture.* 2002;16:1–14.

60 Mitra S, Knight A, Munn A. Divergent effects of cognitive load on quiet stance and task-linked postural coordination. *J Exp Psychol Hum Percept Perform.* 2013;39:323–328.

61 Bourlon C, Lehenaff L, Batifoulier C, et al. Dual-tasking postural control in patients with right brain damage. *Gait Posture.* 2014;39:188–193.

62 Little CE, Woollacott M. Effect of attentional interference on balance recovery in older adults. *Exp Brain Res.* 2014;232:2049–2060.

63 Beauchet O, Annweiler C, Dubost V, et al. Stops walking when talking: a predictor of falls in older adults? *Eur J Neurol.* 2009;16:786–795.

64 Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. *Mov Disord.* 2008;23:329–342.

65 Bowen A, Wenman R, Mickelborough J, et al. Dual-task effects of talking while walking on velocity and balance following a stroke. *Age Ageing.* 2001;30:319–323.

66 Canning CG, Ada L, Paul SS. Is automaticity of walking regained after stroke? *Disabil Rehabil.* 2006;28:97–102.

67 Yang YR, Chen YC, Lee CS, et al. Dual-task–related gait changes in individuals with stroke. *Gait Posture.* 2007;25:185–190.

68 Smulders K, van Swigchem R, de Swart BJ, et al. Community-dwelling people with chronic stroke need disproportionate attention while walking and negotiating obstacles. *Gait Posture.* 2012;36:127–132.

69 Roerdink M, Geurts AC, de Haart M, Beek PJ. On the relative contribution of the paretic leg to the control of posture after stroke. *Neurorehabil Neural Repair.* 2009;23:267–274.

70 Thut G, Hauert C, Viviani P, et al. Internally driven vs. externally cued movement selection: a study on the timing of brain activity. *Brain Res Cogn Brain Res.* 2000;9:261–269.

71 Takeda K, Gomi Y, Imai I, et al. Shift of motor activation areas during recovery from hemiparesis after cerebral infarction: a longitudinal study with near-infrared spectroscopy. *Neurosci Res.* 2007;59:136–144.

72 Kato H, Izumiyama M, Koizumi H, et al. Near-infrared spectroscopic topography as a tool to monitor motor reorganization after hemiparetic stroke: a comparison with functional MRI. *Stroke.* 2002;33:2032–2036.

73 Fang Y, Yue GH, Hrovat K, et al. Abnormal cognitive planning and movement smoothness control for a complex shoulder/elbow motor task in stroke survivors. *J Neurol Sci.* 2007;256:21–29.

74 Wiese H, Stude P, Nebel K, et al. Recovery of movement-related potentials in the temporal course after prefrontal traumatic brain injury: a follow-up study. *Clin Neurophysiol.* 2004;115:2677–2692.

75 Passingham RE. Premotor cortex: sensory cues and movement. *Behav Brain Res.* 1985;18:175–185.

76 Cunnington R, Windischberger C, Deecke L, Moser E. The preparation and execution of self-initiated and externally-triggered movement: a study of event-related fMRI. *Neuroimage.* 2002;15:373–385.

77 Taniwaki T, Okayama A, Yoshiura T, et al. Functional network of the basal ganglia and cerebellar motor loops in vivo: different activation patterns between self-initiated and externally triggered movements. *Neuroimage.* 2006;31:745–753.

78 Richter W, Andersen PM, Georgopoulos AP, Kim SG. Sequential activity in human motor areas during a delayed cued finger movement task studied by time-resolved fMRI. *Neuroreport.* 1997;8:1257–1261.

79 Cunnington R, Windischberger C, Deecke L, Moser E. The preparation and readiness for voluntary movement: a high-field event-related fMRI study of the Bereitschafts-BOLD response. *Neuroimage.* 2003;20:404–412.