Article 25fa pilot End User Agreement

This publication is distributed under the terms of Article 25fa of the Dutch Copyright Act (Auteurswet) with explicit consent by the author. Dutch law entitles the maker of a short scientific work funded either wholly or partially by Dutch public funds to make that work publicly available for no consideration following a reasonable period of time after the work was first published, provided that clear reference is made to the source of the first publication of the work.

This publication is distributed under The Association of Universities in the Netherlands (VSNU) ‘Article 25fa implementation’ pilot project. In this pilot research outputs of researchers employed by Dutch Universities that comply with the legal requirements of Article 25fa of the Dutch Copyright Act are distributed online and free of cost or other barriers in institutional repositories. Research outputs are distributed six months after their first online publication in the original published version and with proper attribution to the source of the original publication.

You are permitted to download and use the publication for personal purposes. All rights remain with the author(s) and/or copyrights owner(s) of this work. Any use of the publication other than authorised under this licence or copyright law is prohibited.

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please contact the Library through email: copyright@ubn.ru.nl, or send a letter to:

University Library
Radboud University
Copyright Information Point
PO Box 9100
6500 HA Nijmegen

You will be contacted as soon as possible.
Motor control and action

Chris Dijkerman and Bert Steenbergen

12.1 Introduction

Motor control is a function that psychologists often do not automatically associate with neuropsychology. Yet there are good reasons for including motor functions in a book on clinical neuropsychology. First, without movement no overt behaviour is possible. Performances on all neuropsychological tests depend on motor output. For example, an impairment in the movement of the preferred hand can have a negative influence on pen-and-paper tests that set out to measure other functions. Motor impairments are also a common phenomenon following a brain injury, and neuropsychologists will often be confronted with these in clinical practice. Some knowledge of motor control and the associated impairments is important for a correct interpretation of behaviour and test results in a clinical setting. Finally, motor control is intrinsically interesting for neuropsychologists, as it is also a cognitive process. For example, consider the planning of successive movements, or imagining a movement that is not actually carried out (i.e. motor imagery).

Movements can be made using various limbs and body parts, such as eyes, hands, arms, and legs. This chapter focuses mainly on hand and arm movements, as these are of most relevance to neuropsychologists. It starts by discussing the organisation of the motor system and the way in which movements are represented, and then covers various impairments that are relevant to neuropsychology.
flexes are at the lowest level. Above these are automated movements, such as posture and the basic aspects of walking. At the highest level are voluntary movements.

From a neuroanatomical point of view there are also three levels. At the lowest level is the activation of the muscles by neurons in the spinal cord. The activity of these neurons is influenced by brainstem nuclei. Finally, these are in turn influenced by the motor areas of the cerebral cortex. In addition, from a neuroanatomical point of view there is also some degree of parallel organisation with various brainstem structures that influence spinal cord neurons and, even more important for voluntary motor control, direct projections from the cerebral cortex to the spinal cord.

12.2.1 The muscles
Movements are carried out via activation of the muscles. When muscles are activated, they contract. A muscle can be passively extended only as a result of the contraction of another muscle, or by passive extension by an external force. Muscles therefore usually work in pairs (agonist-antagonist), with a contraction of one muscle (the agonist) extending the other muscle (the antagonist).

12.2.2 The spinal cord
Muscles receive signals via motor neurons on the ventral side (facing toward the stomach) of the spinal cord. The activity of these neurons can be influenced by neurons at various levels within the central nervous system. First, the motor neurons receive sensory information about the contraction state of particular muscles via muscle spindles located in those muscles. This input is involved in reflex movements, among other processes. Second, the motor neurons receive information from other motor neurons in the spinal cord, as a result of which coordination of muscle activity takes place in part at the level of the spinal cord. Finally, motor neurons, as stated above, receive input from nuclei in the brainstem and from the cerebral cortex.

12.2.3 The brainstem
The main projections from the brainstem to the spinal cord are the reticulospinal, tectospinal, and vestibulospinal pathways (see Figure 12.3). These pathways start in the reticular formation, the tectum, and the vestibular nuclei, respectively. The pathways project bilaterally to the spinal cord and thus innervate motor neurons that activate these muscles on both sides of the body. These neural pathways are involved mainly in posture control and the activation of proximal arm and leg muscles (i.e. those situated nearer to the centre of the body). Projections are not usually direct, but instead travel via interneurons that then project to the motor neurons.

12.2.4 Cortical projections
Various cortical areas are involved in motor control (see Figure 12.2). The most important of these is the primary motor cortex. The premotor cortex and the supplementary motor area (SMA) in the frontal lobe are also important, and finally the parietal cortex is of significance too. Cortical neural pathways that are involved in muscle control project directly to both the spinal cord and the brainstem nuclei referred to earlier in this chapter. Direct corticospinal projections originate from various
Cognitive Domains

The greatest contribution is made by the primary motor cortex. In humans, 60% of corticospinal projections originate from this area, which contains a representation of the body (the homunculus), with the lips, hands, and fingers covering a relatively large area. The size of the different areas is related to the amount of motor input that the various body parts receive. The fingers in particular require more sophisticated control, with the involvement of more neural pathways.

**Figure 12.2** Primary motor and sensory cortex

The direct corticospinal projections also originate from the supplementary motor areas, the premotor cortex, the cingulate gyrus, the primary and secondary somatosensory cortex, and the posterior parietal lobe.

There are two types of corticospinal projections. First, there are neural pathways that terminate on interneurons in the spinal cord, just like the projections from the brainstem. These projections run mainly contraterally and to some extent bilaterally. The neural pathways are involved mainly in muscle control for the torso, shoulders, and upper arm, and to some extent in movements of the whole hand.

In addition, there are mainly contralateral projections from the motor cortex that terminate directly at the motor neurons. These corticomotoneuronal pathways are probably responsible for the ability of monkeys and humans to make individual finger movements (Porter & Lemon, 1993). Moreover, in humans, direct corticomotoneuronal projections are also found for proximal arm and axial torso muscles.

Cortical projections reach the spinal cord indirectly via the brainstem as well. These projections come mainly from areas for the primary motor cortex and terminate in the brainstem nuclei, where the medial descending pathways originate.

It should be clear from the above description that the motor neural system has both hierarchical and parallel organisation. Various neural pathways are thus involved in the activation of the same muscle groups. This applies in particular to the proximal and axial muscles, which receive input from brainstem nuclei and from the cerebral cortex (both directly to the spinal cord and via the brainstem). Some of these neural pathways also project bilaterally, as a result of which proximal and axial muscles receive information from both cortical hemispheres. However, distal movements, particularly individual finger movements, are controlled virtually solely via the direct contralateral corticospinal projections, and are thus more vulnerable following a brain injury.

### 12.3 Representation of movements

So far this chapter has described how the neural system activates muscles. However, this activation has to be controlled by something. Two aspects are important. First, in order to be able to reproduce movements reliably time after time, those movements must be represented in the central nervous system. Second, sensory (visual, proprioceptive, and vestibular) information is used during the execution of a movement to inform us about the movement itself as well as about external objects towards which the movement is aimed (e.g. lifting up a coffee cup). Proprioception enables us...
to obtain information through receptors in joints, muscles, and skin about positions, changes in positions, and bodily movements, and is thus essential for movement. This section covers the representation of movements. Various lines of research have provided us with some insight into how movements are represented in the brain.

12.3.1 Mirror neurons
Research on mirror neurons provides us with information about how movement representations work and are stored in the brain. In the early 1990s, a group of Italian neurophysiologists discovered that certain cells in the prefrontal cortex are active not only during the implementation of visually controlled grasping movements, but also when the same type of movement is observed in someone else (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1998). These cells are called mirror neurons, and they react only during purposeful movements, so they are not active when a hand copies the grasping movement without an object, or when an object is merely within sight. Even the indirect grasping of an object with a tool, such as tweezers, barely activates the mirror neurons. Some neurons are especially sensitive to the grasping movement with just a thumb and forefinger (precision grip), whereas others are sensitive to the grasping movement with the whole hand (power grip). Functional imaging techniques have shown that a similar system is also present in the prefrontal cortex of humans (Rizzolatti et al., 1996). More recent research has shown that other areas of the brain are also active during the observation of an action and the execution of this action. The posterior parietal cortex in particular is now regarded as part of the mirror neuron system. The question is what the function of such a system might be. Perhaps the most obvious suggestion is that it is a vocabulary of movement representations (Rizzolatti & Arbib, 1998). Seeing a movement would directly activate the representation for the execution of the same movement. This can be of major importance for imitation of movements and for understanding the meaning of a particular movement (Binkofski & Buccino, 2006). This system was therefore linked to recognition and implementation of gestures, and is also regarded as a precursor to spoken language in humans (Rizzolatti & Arbib, 1998). Evidence for this comes from fMRI studies which show that Broca's area is active during both the observation of an action and the execution of an action (Iacoboni et al., 1999).

This system is also linked to social cognition and to empathy (Keysers & Gazzola, 2006). The recognition of actions and gestures by another person through internal simulation within the mirror neuron system could be used to understand the intentions of the other person, which can play a role in social situations. Observation of touching also appears to activate neurons in various cortical somatosensory areas (Keysers & Gazzola, 2006). Thus seeing another person being touched results in an experience of being touched, which can be either pleasant or painful. These signals can also be important for experiencing empathy with other people (see also Chapter 11, 'Emotion and social cognition').

12.3.2 Forward models
Another concept that has received increasing attention over the last few years is the forward model. The central idea is that a prediction of the consequences of an action is made on the basis of an internal model of the motor system (Wolpert, 1997). This can be a prediction not only about what the 'next stage' of the motor system is (for example, at what speed the movement should continue, e.g. picking up a cup and bringing one's hand with the cup to one's mouth), but also about the sensory consequences of an action (for example, spilling hot tea on one's hand if one moves too quickly). The latter can be important in enabling a distinction to be made between sensory consequences that are the result of self-controlled movements on the one hand, and of externally controlled movements on the other. This is relevant, for example, in the case of eye movements, where it is crucial to make a distinction between movement input from the retina stimulus (i.e. whether you are turning your head and your eyes move with it, or whether your head is stationary and you are moving your eyes to follow a moving object). A copy of a motor programme, also called an internal copy, can be used to predict the expected sensory consequences and then suppress these. By suppressing the expectation we can perceive specific movement information that is caused by external stimuli, and distinguish between sensory information that is caused by our own actions and sensory information that is caused by stimulation from our external environment. A similar mechanism can play a role in self-touching. Various studies have shown that forward models ensure that we cannot tickle ourselves (Blakemore, Wolpert, & Frith, 1998). Here, too, a touch can be partly suppressed on the basis of expected sensory consequences, as a result of which the sensation of touching oneself feels less intense.

Finally, an impairment in the forward model is related to certain syndromes. For example, Frith, Blakemore, and Wolpert (2000) suggest that control delusions in schizophrenia are caused partly because the forward mechanism is impaired. In these patients the sensory consequences of touching themselves are less suppressed, as a result of which they are more likely to make a distinction between their own actions and those of other people. Together with an exaggerated feeling of agency (the attribution of the causes of a movement to oneself or to someone else), this ensures...
that self-caused sensations and thoughts are attributed to other people.

A second example of an impairment that is related to forward models is developmental coordination disorder (DCD). Children with this impairment have difficulty making rapid online corrections. That is, they have difficulties in making adjustments based on the internal predictive model of an ongoing movement.

12.3.3 Motor planning
As discussed in the previous section, a forward model can be used to predict the sensory consequences of an action. This is in fact motor planning. In broad terms, motor planning can be described as the preparation of an ongoing movement. It is clear that the performance of rapid movements would not be possible if the system had to rely solely on feedback from sensory systems (e.g., visual information, information from the muscle spindles). Therefore before a movement is executed, planning is required. There is still no consensus in the scientific literature about what is planned and at what level this takes place. One way of finding out what motor planning involves would be to seek invariants in the execution of a movement. Manipulations (variants) are introduced into the task—e.g., the distance across which somebody has to reach, or the size of the object that they have to grasp. Then it is noted which aspects of the execution of a movement remain the same (invariants). For example, if the pattern of the movement remains the same (invariants), it can be concluded that the motor plan is based on the end point of the movement itself.

Although the above account discusses motor planning mainly in terms of the execution of movements, theories have recently been developed which assume that motor planning focuses on the end point or objective of the movement. A famous example is the principle of end-state comfort. According to this principle, the end of the movement is planned first, followed by the movement towards it. In contrast to the above mentioned models, the starting point in this model is the end of the movement, not the movement itself. One example of this principle can be observed when a person picks up an upside-down cup and places it on a table the right way up. In this situation people often pick up the cup with a fairly comfortable grip, with their hand in a pronated (upside-down) position, so that the task finishes with a comfortable grip. This observation, which has been confirmed several times in experiments, indicates that people plan in terms of the comfort of the end posture (i.e., the motor plan focuses on the end point).

12.3.4 Motor imagery
A third line of research that provides insight into how movements are represented in the brain focuses on imagining movements, also called motor imagery. Jeannerod (1997) suggested that motor imagery occurs as a result of making conscious representations of movements that are largely unconscious. The imagined movements are thought to have the same characteristics as the underlying motor representations of those movements. The imagining of movements is based on the same functional mechanisms as those used when actually executing the movements. This makes the study of imagined movements a suitable method of studying representations of movements.

One example of this is research into changes in the time that is required to execute a movement whenever a task changes. For example, if a test subject is asked to point to a circle, the movement will take longer if the circle is smaller (this is known as Fitts's law). This effect is also observed when the pointing movement is carried out only in the imagination (Jeannerod, 1997). In general, it can be stated that motor imagery activates many cortical areas that are also involved in the actual execution of the movement, but that specific activations also occur during the imagery. The latter occur mainly within the primary somatosensory and motor areas and in the anterior cerebellum (Hanakawa et al., 2003). For instance, it has recently been shown that pictures of hands that are turned inward are recognised faster than pictures of hands that are turned outward (Ter Horst, Van Lier, & Steenbergen, 2011). This corresponds to the biomechanics of actual hand movements.

Finally, research conducted among neurological patients shows that although motor impairments often affect execution and imagination to the same extent, there are also dissociations. For instance, a patient with a parietal lesion was described who could make movements but who could no longer accurately estimate the duration of movements, and therefore had problems imagining movements. Problems with imagining movements have also been demonstrated in the case of congenital cerebral paresis, and the right hemisphere in particular appears to be involved (Steenbergen, Van Nimwegen, & Crajé, 2007). However, there are also descriptions of patients who can imagine movements but are unable to execute these with their hemiplegic hand (Johnson, 2000).

12.4. Representation of targets (and movement targets)

12.4.1 External representation of targets (and movement targets)

Perhaps the most important function of movement is to be able to interact effectively with the environment. For instance, we are able to pick up ob-
projects and walk through rooms that contain all kinds of obstacles that we need to avoid. This effective interaction with our surroundings is only possible if sensory information about our surroundings can be linked in the brain to the motor system. Neuropsychological, neurophysiological, and neuroimaging research suggests that the posterior parietal lobe plays an important role in this. The most important sense for obtaining information about the environment is the visual system. As described in Chapter 6 (‘Visual perception’) and Chapter 7 (‘Spatial cognition’), visual information is received by the primary visual cortex and is then further processed along two routes. The ventral route (the ‘what’ route) terminates at the inferior part of the temporal cortex, whereas the dorsal route (the ‘how’ route) goes to the superior part of the posterior parietal lobe (Milner & Goodale, 1995). The ‘how’ route is important mainly for visually controlled movements. Neurons in the posterior parietal lobe have both visual and motor characteristics. The posterior parietal lobe is also involved in the integration of proprioceptive and tactile information from the moving arm (Dijkerman & De Haan, 2007). Different visuomotor pathways are probably involved in the conversion of visual signals into a motor output. For instance, visually controlled neurons have been found in the posterior parietal lobe that are also active during the execution of eye movements or saccades, whereas other neurons react during eye-tracking movements. With regard to the arm, a distinction can be made between reaching (taking the hand to the object) and gripping (opening the hand). These observations from neurophysiology have been confirmed by studies of patients with posterior parietal lesions which can selectively impair reaching or gripping movements (see also the discussion of ‘Optic ataxia and Bálint’s syndrome’ under Section 7.2.4 in Chapter 7, ‘Spatial cognition’).

One problem with visually controlled movements is the use of different reference frameworks. Visual information is first of all represented retinotopically—that is, in accordance with a map of the retina (see Chapter 6, ‘Visual perception’). However, in order to programme a grasping movement, an arm-centred representation of the object of the movement is necessary. There are two possible solutions to this problem. First, there is neurophysiological evidence that proprioceptive information about the position of the eyes in relation to the head is used to obtain a head-centred representation of the target object. Proprioceptive neck and vestibular signals can be added to this in order to obtain a body-centred representation (Andersen, 1997). A second solution comes from neurophysiological research, and fMRI and patient studies, which suggest that visual information for arm movements can also be encoded in an eye-centred representation (Khan et al., 2005). The advantage of this is that eye and hand movements, which are often made together (one often looks at the object that one is going to pick up before one reaches for it), can use the same representation.

12.4.2 Internal representations of targets (of movements)
Although processing of visual information in the posterior parietal lobe is associated mainly with motor actions, this does not mean that the ventral route is not important for visuomotor control. The ventral route is involved in particular in movement control when information about the object has to be remembered for some time and is thus no longer visible (Goodale, Jakobson, & Keillor, 1994). The ventral route also plays a role if semantic information about the target object is important, or if there is only monocular depth information (Dijkerman, Milner, & Carey, 1996).

Various authors have recently proposed that the dorsal route can be further classified into a dorso-dorsal and a ventro-dorsal route, with the latter containing mainly the inferior posterior parietal lobe. The ventro-dorsal route is important primarily in spatial perception (right hemisphere; see ‘Neglect’ under Section 7.2.2 in Chapter 7, ‘Spatial cognition’) and in the understanding and recognition of movements and the function of objects (Rizzolatti & Matelli, 2003) based on conceptual and semantic input about actions and objects (left hemisphere; see also Section 12.5.2 later in this chapter) (Buxbaum & Kalenieke, 2010). The dorso-dorsal route is concerned mainly with the processing of sensory (somatosensory and visual) information for controlling purposeful reaching and grasping movements.

12.5 Impairments
For movement control, sensory information is required not only about the target of a movement in the external world, but also about one's own body. A person who is about to grasp a cup has to know where their hand is in order to be able to actually make this movement. A representation of the body that is used in movement control is also called a body schema. This term was first used a century ago by Head and Holmes (1911-1912) in their description of sensory impairments following a brain injury. Although definitions have differed somewhat in the past, at the time of writing a distinction is made between body schema and body image, which is a representation that is used mainly for the conscious perception of the body (Dijkerman & De Haan, 2007). Over the last decade in the cognitive neurosciences there has been renewed interest in conceptual and neural representations of the body, and the body schema is part of this. The body schema is characterised by bottom-up processing of sensory information that is constantly updated and is not accessible to conscious perception.
This is demonstrated, for example, by research on body-related illusions, such as the rubber hand illusion (see Box 12.1) and the vibrotactile illusion. In both of these illusions the test subject feels as if the position of the hand has been moved (due to an influence on the body image), while movements are still executed accurately. The superior posterior parietal and premotor areas are involved primarily in the body schema.

12.5.1 Cerebral palsy and hemiplegia

Cerebral palsy (CP) is an umbrella term for a group of chronic, non-progressive impairments in motor control and muscle coordination that result in restrictions in the implementation of daily activities. The impairments are the result of damage to the motor areas of the brain during fetal development, or before, during, or immediately after birth, or during the first year after birth. The impairment is non-progressive, but the clinical picture changes as a result of the development of the central nervous system and the brain. The prevalence of CP in developed countries is estimated to be 1.4-2.7% of live births. The causal factors may be present before birth (complications during pregnancy, such as infections and encephalitis), during birth (oxygen deprivation or head trauma during birth, or extremely premature birth combined with a low birth weight), or after birth (accident or illness). CP is an impairment that is primarily of a motor nature, but that can be accompanied by different comorbidities, such as epilepsy, visual impairments, cognitive-function impairments, hearing impairments, feeding problems (difficulty in swallowing), and emotional and behavioural problems. Various signs in early development can indicate CP, including slow development, the delayed achievement of gross motor milestones, abnormal muscle tension (hypotonia or hypertonia), abnormal posture and reflexes, reduced movement quality, and early development of hand preference. This is a very heterogeneous group with many manifestations. The majority (around 75%) have spastic CP, around 20% have dyskinetic CP (constant movements as a result of continuous changes in muscle tension), and less than 5% have ataxic CP (irregular movements).

The group with spastic CP can be divided into two categories – unilateral (one-sided impairment, known as hemiparesis) and bilateral (two-sided impairment, when both arms and/or both legs are affected; in the case of diplegia it is mainly the legs that are affected, and in the case of tetraparesis both the arms and the legs are affected). Spasticity is characterised by an increased speed-dependent resistance of the muscles to passive extension. In the muscles that act as antagonists in a movement there is increased muscle tension in particular, as a result of which movements are 'sluggish.' The degree of spasticity can be determined using the Modified Ashworth Scale (MAS) for grading spasticity (Pandyan et al., 1999).
The Gross Motor Function Classification System (GMFCS; Palisano et al., 2000) is also used to chart what children are able to do in broad motor terms at a particular age.

Another common motor impairment is developmental coordination disorder (DCD), which also used to be known as minimal cerebral palsy. The prevalence of this impairment is around 5-10%. It is characterised by motor clumsiness, without any demonstrable neurological abnormality, as is the case with CP. The motor impairments in this group are less severe than in CP. DCD is often diagnosed using the results of the Movement Assessment Battery for Children (Movement ABC). This is a test used to determine premature motor restrictions in children. The task measures three components (manual dexterity, aiming and catching, and balance), divided over eight items. In the Netherlands there are standard scores for this test so that it can be determined whether motor control falls within this standard.

12.5.2 Apraxia

Apraxia can be defined as an inability to carry out purposeful behaviour in the absence of a paralysis or paresis. Patients with apraxia have problems executing movements on command, imitating movements, using items such as tools, making gestures, and planning and implementing various movements one after another (movement sequences). Apraxia is usually associated with lesions in the left parietal lobe, but can also occur following injury to the right parietal regions, the temporal and frontal cortex, and even after subcortical lesions in the white matter and the basal ganglia. Impairments following lesions in the right hemisphere occur mainly in tasks that depend more on spatial processes (e.g. when imitating finger movements rather than hand movements).

Apraxia is a common impairment. Deficits in the imitation of movements and in the depiction of the use of certain objects (pantomime) occur in one-third to half of all patients with lesions in the left hemisphere. This figure rises to two-thirds of patients with aphasia (De Renzi, Faglioni, & Sorgato, 1982), which does not mean that apraxia and aphasia are part of the same syndrome. Aphasia can occur without apraxia, and vice versa.

The term ‘apraxia’ was used for the first time by the German linguist Chaim Steinthal in 1871. The work of the German neurologist Hugo Liepmann was particularly influential (see Box 12.2). He conducted several systematic studies into apraxia at the beginning of the twentieth century.

On the basis of these studies, Liepmann formulated ideas about apraxia that are still extremely influential today. The idea that apraxia is associated mainly with lesions in the left hemisphere was mentioned earlier. Liepmann also distinguished between different types of apraxia. Perhaps the most well-known example is his study of a 48-year-old civil servant, T., who was right-handed, had an infarction in December 1899. He had motor aphasia and a temporary problem with walking, and he had difficulty standing without help. He also needed to be fed. He was anxious and could not move his arms and legs properly. After four weeks he could say no words except for ‘Yes’ and ‘Ah.’ He could write his name to some extent, but he could not copy words or drawings. Between March and October 1900 there was some improvement. In October 1900, T. had another infarction, followed by another in early 1902. He died on 8 April 1902.

Figure 12.4 Hugo Liepmann

Hugo Liepmann (1863–1925) first saw patient T. on 17 February 1900. When T. had to pick up and hold objects, he did this in a strange way. Initially it appeared that he did not understand the tasks or could not see properly. However, Liepmann noticed several strange movements of the right arm. Movements of the whole body, such as standing up or walking to the window or the door, were executed correctly. So it was clear that T. could understand the tasks. Liepmann then asked him to perform several tasks using his left hand, and he was able to do these, too. The same observation was made for his legs and feet. He could not do the tasks with his right leg or right foot, but he had no problems with his left leg and left foot. T. was asked to comb his hair. Usually he did not react, but when he was asked to comb his hair with his left hand, he did this correctly. Then Liepmann told him to comb his hair with his right hand. T. picked up the comb, held it against his hair with the back of his hand against his ear, stuck it behind his ear like a pen, and then seemed satisfied with what he had done. Liepmann described many similar observations, which he initially regarded as bizarre. As the patient could execute certain movements (e.g. walking) properly, and the movement problems were restricted to one side of the body, Liepmann concluded that there could not be a problem with understanding the tasks, and that there must be
something wrong with the control of the execution of purposeful movements. He called this impairment apraxia.

Liepmann distinguished between different forms of apraxia, such as motor apraxia (more or less restricted to a certain part of the body) and situational apraxia (a more general problem with performing certain actions). An important conclusion was that only deliberate movements could no longer be executed properly: 'Apraxia is the loss or disruption of movements learned through experience, examples or lessons, thus something that is exclusively mnestic. If we take the entirety of the former mechanisms of the executive instrument into account, it would mean that something superordinate to the executive instrument is affected in apraxia.' (Gonzalez-Rothi & Hellman, 1996).

Two best-known types are ideomotor apraxia and ideational apraxia. The latter is traditionally defined as an impairment in the conceptual representation of movements. These patients have impairments in the execution of meaningful movement sequences and the use of tools, although their ability to imitate movements is relatively intact. In addition to ideational apraxia, which is an impairment in the execution of movement sequences, nowadays conceptual apraxia is also distinguished, which is an impairment of the concept of the movement (Koski, Iacobini, & Mazziotta, 2002). In the case of ideomotor apraxia the representation of movements is intact, but this can no longer reach the premotor and primary motor areas, which means that imitation is also impaired. Patients with ideomotor apraxia can form a concept of the action to be carried out, as a result of which they can recognise the function of certain tools, but they cannot use these tools correctly. Their movements are often characterised by temporal abnormalities (irregular speed) and spatial abnormalities (in the amplitude of the movement, and impaired spatial configuration of objects and body parts during the movement). This is the most common form of apraxia, and it is linked to left parietal and frontal lesions. Recent lesion overlap studies have demonstrated that left parietal damage is related mainly to impairments in tool use and imitation of unfamiliar hand gestures, whereas inferior frontal lesions in the left hemisphere are related to impairments in the execution of familiar hand gestures (Goldenberg, 2009).

Over the years, various other types of apraxia have been described (see Table 12.1). These can be distinguished from each other on the basis of the modality (visual or tactile), the part of the body (limbs or face), and the type of movement (imitation, movement sequences, use of objects, recognition, or making of gestures) that has been affected. It should be clear that the different types of apraxia are not mutually exclusive categories. For example, ideomotor apraxia can occur both in the arms (limb apraxia) and in the face (buccofacial apraxia).

<table>
<thead>
<tr>
<th>Type of apraxia</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on movement type</td>
<td></td>
</tr>
<tr>
<td>Ideomotor apraxia</td>
<td>Problems with the execution of movements based on verbal instructions or imitation, usually characterised by spatial and temporal errors in the execution of movements.</td>
</tr>
<tr>
<td>Ideational apraxia</td>
<td>Impairment in the execution of movement sequences, originally also used to denote problems in representation of action concepts.</td>
</tr>
<tr>
<td>Conceptual apraxia</td>
<td>A movement impairment in which the concept of the movement has been lost. It is characterised by problems with the use of tools and the understanding of gestures.</td>
</tr>
<tr>
<td>Conduction apraxia</td>
<td>Problems with the imitation of movements, although the depiction of movements is relatively intact.</td>
</tr>
<tr>
<td>Pantomime apraxia</td>
<td>Impairment in visually distinguishing between and the understanding of gestures, with the imitation of the gestures being relatively intact. The recognition of objects is not impaired.</td>
</tr>
<tr>
<td>Limb-kinetic apraxia</td>
<td>Slowness and stiffness of movements, with a loss of fine, precise movements.</td>
</tr>
<tr>
<td>Constructive apraxia</td>
<td>Impairment of the ability to assemble different parts to form a whole (see also Section 7.2.4).</td>
</tr>
<tr>
<td>Based on body part</td>
<td></td>
</tr>
<tr>
<td>Limb apraxia</td>
<td>Normally used to denote ideomotor apraxia of the limbs; this usually includes impaired movements of the hands and fingers.</td>
</tr>
<tr>
<td>Buccofacial apraxia</td>
<td>Impairment in the execution of mouth and facial movements on command or in imitation.</td>
</tr>
<tr>
<td>Orofacial apraxia</td>
<td>Impairment in the execution of mouth and facial movements based on verbal instructions or imitation (see also buccofacial apraxia).</td>
</tr>
<tr>
<td>Optic apraxia</td>
<td>Problems with the execution of saccades based on verbal instructions.</td>
</tr>
<tr>
<td>Speech apraxia</td>
<td>Selective impairment of the ability to produce speech sounds.</td>
</tr>
<tr>
<td>Based on sensory modality</td>
<td></td>
</tr>
<tr>
<td>Unimodal apraxia</td>
<td>A form of apraxia in which actions within one modality are impaired (i.e. apraxia based on visual but not auditory input, etc.).</td>
</tr>
<tr>
<td>Tactile apraxia</td>
<td>Problems with the execution of hand movements during tactile interaction with an object, although gestures can be performed well.</td>
</tr>
<tr>
<td>Disconnection apraxia</td>
<td>Apraxia as a result of a disconnection between a specific type of input and motor representations. The input can be verbal (movements cannot be made on command), visual (tool, imitation), or tactile.</td>
</tr>
</tbody>
</table>

Various models have been developed that aim to match the impaired processes with the different forms of apraxia (see, for example, Goldenberg, 2009). Most of these models are related to a greater or lesser extent to Liepmann's original model. However, an important amendment is that in addition to an indirect route, which runs via conceptual knowledge to the gestures and movements to be performed, there is also a direct visual route, in which visual information is directly converted into a movement. This route is particularly important in the imitation of unfamiliar gestures.
Patients have been described who could imitate gestures without recognising them (Rothi, Ochipa, & Heilman, 1991). The ability to perform unfamiliar gestures is consistent with evidence about mirror neuron representations.

**Figure 12.5 Sensorimotor information processing**

A model of sensorimotor information processing for apraxia. In addition to an indirect route in which auditory and visual information activates representations of actions in the lexicon, there is also a direct route from visual information to motor output (innervatory patterns) (Roth et al., 1991).

With regard to making a movement towards an object, a distinction can be made between action representations based on the structure of the object and those based on the function of the object (Vingerhoets, Acke, Vandemeule, & Achten, 2009). The latter would be impaired in particular in the case of apraxia following an injury to the left inferior posterior parietal cortex. Object representations based on structure are thought to be impaired primarily following dorso-dorsal damage, and result in optic ataxia (see Section 7.2.4 in Chapter 7, ‘Spatial cognition’).

Finally, Goldenberg (2009) developed an alternative hypothesis for the involvement of the left posterior parietal cortex in the case of apraxia. He observed that the imitation of meaningless gestures and object usage in particular is impaired following injury to these brain areas. He therefore proposed that the left posterior parietal cortex is involved in categorial spatial representations of object to body part or body part to body part relationships.

### 12.5.3 Optic ataxia

Optic ataxia was first described almost 100 years ago as part of a range of impairments that later became known as Bálint's syndrome. Rezső Bálint had described a patient who had problems pointing to visual objects, but who was able to indicate tactile or aural objects accurately. As described previously in Chapter 7 ('Spatial cognition'), optic ataxia is related mainly to injury to the visual dorsal (or dorso-dorsal) route (Rizzolatti & Matelli, 2003).

### 12.5.4 Alien hand syndrome

A concept that is closely related to body schema is agency, which is the subject’s feeling that they are the person causing the hand movement. This concept is impaired in patients with alien hand syndrome (AHS), which is characterised by involuntary, apparently autonomous movements of the affected hand that occur despite what the patient reports verbally to be their intention, as if the hand is controlled by an external force (Kikkert, Ribbers, & Koudstaal, 2006). Various symptoms can be distinguished, including a grip reflex (the ‘alien hand’ automatically grasping objects in the surrounding area), intermanual conflict (the movements of the affected hand interfering with those of the unaffected hand, such as undoing shirt buttons that have just been fastened by the unaffected hand), and mirror movements (both hands involuntarily performing the same movements). If the patient is aware of the alien hand, this impairment is also called anarchic hand syndrome. This occurs following an injury to both the left and the right hemisphere, especially if the corpus callosum is also affected. Following selective damage to the corpus callosum it is almost always the left hand that is impaired, as if the higher-order intentional motor centres in the left hemisphere are no longer in contact with the lower-order motor output centres in the right hemisphere. This is often characterised by intermanual conflict. A distinction can also be made between anterior frontal AHS and posterior AHS. Frontal AHS is mainly the result of injury to the supplementary motor area (SMA). This affects the grasp reflex and compulsive tactile exploration in particular. This is to some extent similar to the utilisation behaviour following frontal injury as described by Lhermitte (1983), but restricted to one hand. It can indicate an impairment in exogenous top-down movement control, while the exogenous, bottom-up movements triggered by the environment remain intact and are dominant. Posterior AHS is characterised by a feeling of alienation, less complex movements such as levitation (floating), hostile movements (repelling), and stimulation of the affected side (Kloesel, Czarnecki, Muir, & Keller, 2003). AHS can also occur following subcortical (thalamus) lesions and in the case of corticobasal degeneration.
12.6 Conclusion

This overview presented in this chapter demonstrates that motor control is much more complex than the mere control of movements. It is closely interwoven with various sensory and cognitive functions. The processing of visual and somatosensory information about objects in the surrounding area and one's own body is an integral part of movement control. Representations of actions in the brain are not only important for the preparation and execution of movements, but are also related to various cognitive functions, including language, attention, and social cognition. Motor representations can even be activated without any movement being executed, when a person simply thinks about or observes a movement. Over the last few decades there has been a clear shift with regard to the positioning of motor control, which is taking on an increasingly central role in cognitive neuropsychology and the neurosciences. A good example of this is the emergence of the concept of embodied cognition, whereby higher-order cognitive functions can always be based on body-related processes and in particular action-related processes.

This growing interest in and knowledge about the link between cognition and action also has consequences for our understanding of neuropsychological impairments. There are clear opportunities for rehabilitation in particular. For instance, the repeated mental imagining of movements can perhaps activate the damaged neural motor representations and thus promote recovery. The same is true of action observation (Mulder, 2007). These concepts will also be important for many clinical populations in which motor impairments are the main focus. It is becoming increasingly clear that the distinction between perception and action is less strict than was originally believed when it was first formulated over 20 years ago by Milner and Goodale (1995). Motor control is influenced by several representations, some of which represent mainly the structure of the object (dorso-dorsal route), while others represent mainly the position of the limbs (body schema), or knowledge about objects (ventro-dorsal route). The idea is that these representations should be combined flexibly, depending on the requirements of the motor task that has to be performed. The challenge for the immediate future will be to study how these different representations and the underlying neural networks interact with each other.

13 Intelligence

Paul Eling and Joukje Oosterman

13.1 Introduction

The section of this book to which this chapter belongs focuses on psychological functions, in particular cognitive domains. So in many ways it seems obvious that a chapter on intelligence should be included here. But what is the relationship between cognitive functions such as attention, executive functions, and memory on the one hand, and intelligence on the other? Some people believe that intelligence is in fact the sum of the cognitive functions that we use to acquire knowledge and solve problems. This brings us to the fundamental question: what exactly is intelligence?

This chapter discusses a number of different views about what constitutes intelligence, describes several ways of measuring it, examines in more detail the biological basis of intelligence, and finally considers how intelligence is measured in neuropsychological practice. For further information about all aspects of intelligence, the reader is referred to Hunt (2011).

13.2 Two views of intelligence

There are various approaches to the question of what constitutes intelligence, but two views are predominant. According to one view, intelligence is a basic characteristic, the so-called g-factor, which is responsible for inter-individual differences in cognitive performance. It is often unclear what exactly this factor entails. An important argument in favour of this interpretation is that all kinds of cognitive tests correlate with each other. According to the other view there is not one general intelligence, but rather general cognitive domains, and there can be inter-individual differences in each domain; intelligence consists of various distinguishable qualities. Each of these approaches is explained briefly below from a historical perspective.