White, B.J., Boehnke, S.E., Marino, R.A., Itti, L. and Munoz, D.P. (2009) 'Color-related signals in the primate superior colliculus', *J. Neurosci.*, 29: 12159–66.
Wickens, J.R. (2009) 'Synaptic plasticity in the basal ganglia', *Behav. Brain Res.*, 199: 119–28.
Wickens, J.R., Reynolds, J.N.J. and Hyland, B.I. (2003) 'Neural mechanisms of reward-related motor learning', *Curr. Opin. Neurobiol.*, 13: 685–90.
Wightman, R.M. and Robinson, D.L. (2002) 'Transient changes in mesolimbic dopamine and their association with 'reward'', *J. Neurochem.*, 82: 721–35.
Wise, R.A. (2004) 'Dopamine, learning and motivation', *Nat. Rev. Neurosci.*, 5: 483–494.
Wunderlich, K., Rangel, A. and O'Doherty, J.P. (2010) 'Economic choices can be made using only stimulus values', *Proc. Nat. Acad. Sci. USA*, 107: 15005–10.

7

THE ROLE OF AUGMENTED FEEDBACK IN HUMAN MOTOR LEARNING

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Introduction

As kids, we were playing a game called 'Hit the pot' where a pot was placed somewhere on the floor in a room by one child. The challenge for another child was to search for the pot, while crawling on the floor, making knocking movements using a wooden spoon. A tinny sound indicated when the pot was hit. Not a very challenging game, you may argue, because one instantly sees where the pot was placed. However, you miss the important information, that the kid who was searching for the pot was blindfolded.

The word 'blindfolded' could technically be described as 'the temporary loss of visual (sensory) feedback'. As in our example, sensory feedback helps us to move successfully, and also to acquire new motor skills and refine existing skills. This chapter focuses on sensory feedback, more specifically a particular kind of sensory feedback called augmented feedback, and discusses its influence on motor learning. Note that although different types of learning have different substrates, in this chapter we do not distinguish between 'motor adaptation', often associated with the refinement of existing movements, and 'motor learning', the acquisition of new movements (i.e. skill learning), but instead use the term 'motor learning' for all processes.

Sensory feedback arises from many sources in our human body, including e.g. audition, vision, proprioception, or tactile sensation. The sensory feedback serves to inform us about ourselves, and our environment. In this case, 'ourselves' specifically means the state of our own body, and the 'environment' specifically reflects the state of the external world in which we are moving. These are the two important divisions of interest (Wolpert & Ghahramani 2000). For instance, with respect to the state of our body, sensory feedback informs us whether our arm is flexed or extended while crawling over the floor. With respect to the state of the external world, sensory feedback informs us whether there is a couch or a chair in between us and the pot.

Internal intrinsic, internal extrinsic, and augmented feedback

Given the many types of sensors with many different origins, how can sensory feedback be classified? First, sensory feedback can be subdivided into the modality or source of the information, e.g. whether the information originates from vision, audition, or proprioception. Besides this categorization, sensory feedback has traditionally been divided with respect to the division of interest (Schmidt & Lee 1999). There are basically three subdivisions, called (a) internal intrinsic, (b) internal extrinsic, and (c) external (augmented) feedback (see Figure 7.1).

The first subdivision (a) is the sensory feedback informing us about the state of our own body. This was exemplified with the estimation of the state (simplified as an extention or flexion) of our own arm. This estimation can be performed with several sources like proprioception, vision, either alone or in combination. Combining more sources may improve the estimate. The reason for this was argued to be the noisiness of sensory signals processed in the human body (Faisal et al. 2008) and the reduction of noise when using multiple signals with different qualities and therefore noise profiles (Ernst & Banks 2002).

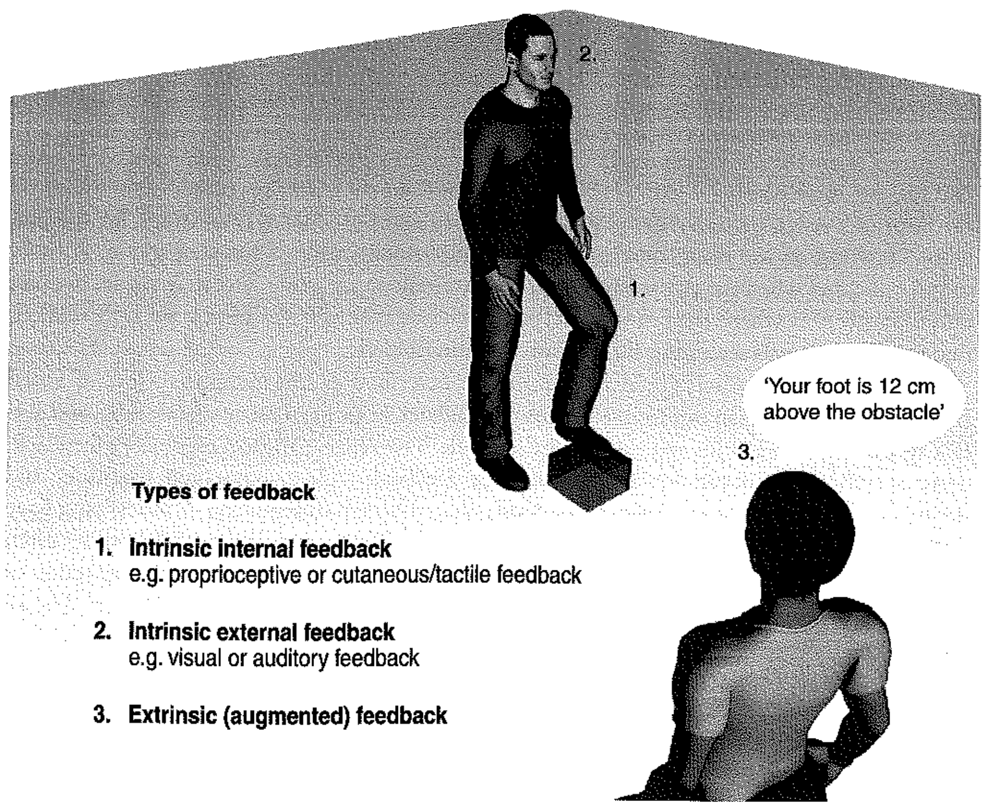

Figure 7.1 Types of feedback. Different types of feedback may be an inherent or intrinsic part of the motor task. The intrinsic feedback may originate from internal inputs e.g. from proprioception and/or external inputs e.g. from visual or auditive feedback. In addition to the intrinsic feedback, augmented feedback may be provided.

The second type of sensory feedback is intrinsic external feedback (b), informing us about the state of the external world. Again, as with intrinsic internal feedback, the estimation of the nature of our environment can be done with a single source, e.g. vision, but is often performed with multiple sources of information. The reason for it is, again, to improve the estimate. As an example, seeing and hearing an approaching train is better with regards to its location and speed than just seeing or hearing it.

In addition to these two types of feedback through which we continuously monitor ourselves and the surrounding world there is a specific type of feedback, called extrinsic feedback or augmented feedback (c) (see Figure 7.2). This type of feedback informs us how we interacted with the external world and it is therefore particularly relevant in all motor learning

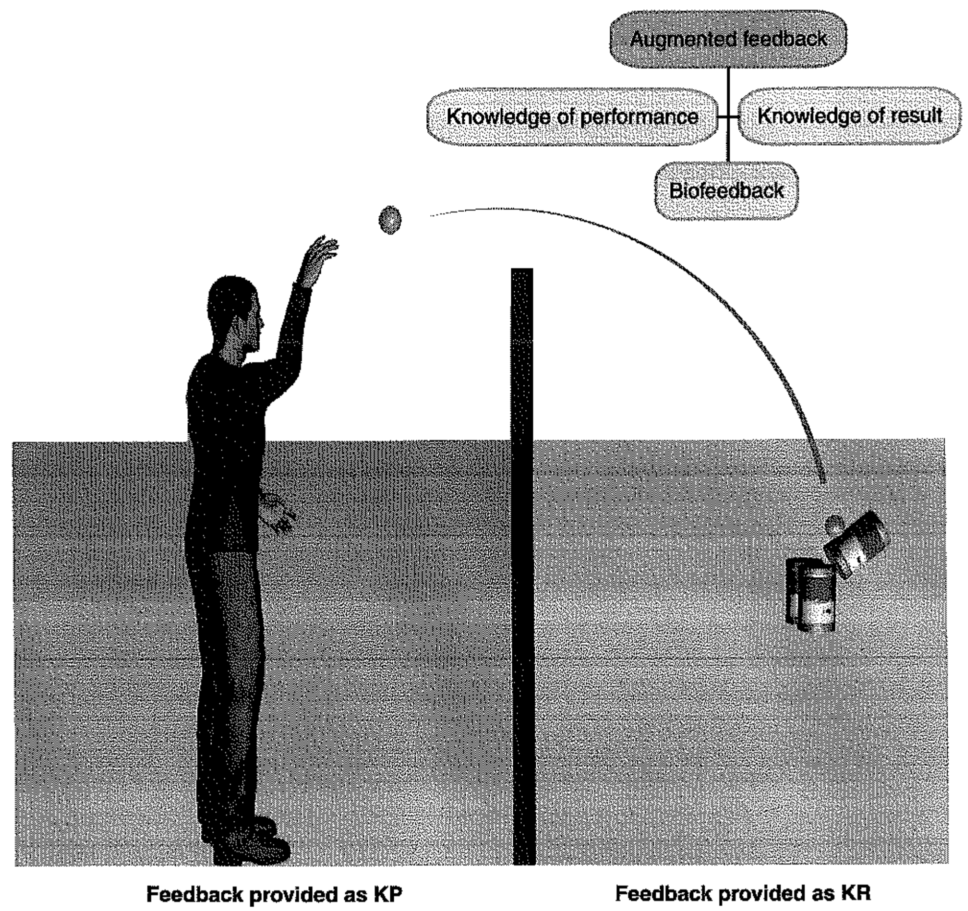

Figure 7.2 Augmented feedback. Augmented feedback may be provided to the learner based on different parameters during motor learning. Knowledge of Result (KR) is information given to the learner after completion of a movement, which describes the outcome of the movement in terms of the movement goal. Knowledge of Performance (KP) is information that describes the quality of the movement pattern that led to the performance outcome. KP differs from KR in terms of what aspects of performance the information refers to. In addition to performance and outcome, feedback may be given based movement kinematics, EMG etc. as biofeedback.

settings (Adams 1987). In the following, we will just use the word 'augmented' feedback, which equals the expression 'external'. The adjective 'augmented' refers to adding or enhancing feedback with an external source, providing an explicit (quantified) knowledge of the result(s) of the motor performance. In other words, augmented feedback informs the person about how well (in quantitative terms) the task was performed (Winstein 1991). Importantly, this information is adjusted to explicitly guide the acting person in improving the motor outcome. As an example, informing a basketball player whether the basket was hit or not provides a simple form of augmented feedback. This simplicity can be arbitrarily increased: for instance, by providing the basketball player with distance errors (30 cm left, 15 cm below) relative to the basket.

Why augmented feedback?

Many experimental, especially motor learning, studies concentrated on augmented feedback because it is better controllable in quantitative terms and can be modified in an experimental setting. In contrast to intrinsic internal and intrinsic external feedback, the intensity of augmented feedback is better controlled on an inter-individual basis. The perception of the arm while shooting a basketball may differ between persons. Consequently, the same angularity of the elbow joint may lead to differences in the sensation of the angularity. On the contrary, augmented feedback about the distance error between the ball and the basket is definite information.

Furthermore, this controllability allows modification(s) of the feedback. This characteristic of augmented feedback was used in many studies aiming to investigate how the nervous system learns movements. For instance, a recent, frequently used paradigm has been the so-called 'visuomotor rotation', where subjects start a drawing or reaching movement from a centre point of a circle to target locations equally placed on the outer bound of a circle (Krakauer 2009). The subjects typically cannot see their moving hand drawing on a touchpad or interacting with an arm of a robot but instead see the projected position of their hand in a virtual setup on a computer screen. While aiming to a target, subjects receive visual feedback about trajectory and/or the endpoint of their movement. In particular, the error between their movement endpoint and the target provides explicit and quantitative information about the performance guiding future movements and can therefore be ascribed to augmented feedback. Now, the position of the target can be rotated artificially so that straight movements of the hand will result in a line deviated by 45° to the left on the computer screen. Subjects will use the explicit visual information on the computer screen to adapt their motor behaviour and will end by making deviated movements of 45° rightwards (compensate) to reach the target.

A final argument for using augmented feedback is that it is very powerful to facilitate performance. There are even some learning paradigms where performance enhancements are difficult with just intrinsic internal and intrinsic external feedback. Learning to improve fast ballistic contractions with the foot requires a quantified feedback of the acceleration of the contraction. This information is provided to the learner. Previous studies investigated the effect of few (30–50) ballistic contractions (called short term learning) on performance enhancements (Lundbye-Jensen et al. 2011). Considerable improvements in performance were only seen when augmented feedback was provided. This feedback consisted of a visual presentation of the mathematical calculation of the acceleration of the movement after each contraction. We will come back to the importance of augmented feedback for performance improvements in more detail later in this chapter.

Augmented feedback and different processes of learning

So far, we have used the term 'motor learning' to refer to the process of performance improvement due to repetitive motor practice. However, there have been different processes of motor learning described in the literature (Wolpert et al. 2011). One process is called reinforcement learning. It refers to a formation of directed action selection based on rewards, and was extensively discussed in the previous chapter. In reinforcement learning, augmented feedback may be provided to facilitate the change in behaviour. Specifically, additional explicit information about behaviour (e.g. whether or not a playground swing went higher (Wolpert et al. 2011)) may help to bias future behaviour (e.g. that the playground swing actually will go higher). The information provided to the acting person in reinforcement learning is, however, limited. Basically, the content of the information is success or failure. In contrast, augmented feedback can contain richer information in an error-based learning process (Wolpert et al. 2011). A classical error-based paradigm has been discussed above. In visuomotor rotation, the learner receives an explicit error signal, indicated by the distance between the target and the endpoint of the movement to the target. This distance can be mathematically described, as, for example, 15 mm to the left and 33 mm below. Thus, in error-based learning, augmented feedback can be easily and extensively used to minimize the error. In our example, minimizing the error in a visuomotor rotation paradigm would mean to directly hit the target.

A third learning process is use-dependent learning. Use-dependent learning means that behaviour can change by pure repetition of (a) specific movement(s) (Wolpert et al. 2011). The person who performs the movement(s) does not receive any information about the outcome. Consequently, augmented feedback is – by definition – not part of the process of use-dependent learning.

Knowledge of performance versus knowledge of result

When mentioning the visuomotor rotation paradigm, we discussed exactly two forms of augmented feedback, which are differently treated in the literature. First, there is the error *while moving* towards a target, referring to the deviation between the trajectory made by the learner and the desired trajectory (e.g. a straight line between the starting point and the target). Second, there is an error *when the movement is finished*, meaning the deviation between the movement endpoint and the target. Traditionally, the first error has been called 'knowledge of performance' and the second has been called 'knowledge of result' (KR) (see Figure 7.2).

The term knowledge of performance refers to feedback on the sequence of the movement. A synonym of knowledge of performance is 'kinematic feedback' (Schmidt & Lee 1999) as the kinematics (path and time) of the moving body are the basis for this form of augmented feedback. For instance, a tennis player aiming to serve a ball could be informed about the paths relative to time of the moving arm and hand. Now, one may argue that the terms paths and time are very imprecise. Specifically, the question is on which parameter one should focus while serving: Should it be the elbow angle while the arm swings up to hit the ball? Or should it be something else? Especially in practical settings like a tennis serve, the determination of parameters is not easy. One problem of the determination relates to the fact that there exist multiple degrees of freedom to perform an action with the same outcome (Bernstein 1967). In other words, in a movement like a tennis service, the trajectory of a hand can look different in-between players but the endpoint (and even the motor outcome, e.g. the speed of the ball or the final destination) could be the same.

In contrast to the difficulties with knowledge of performance as augmented feedback, the variable KR is much clearer. KR provides explicit information about the result(s) of the accomplished movement. In a tennis serve, this explicit information could be whether the ball hit the ground within the opposite service box. Here, the word 'explicit' has to be emphasized. Otherwise, it could be just intrinsic external feedback as the tennis player immediately sees whether the ball hits within the service box after the serve. Explicit information in this example could mean that the coach tells whether the ball was in or out of the service box. As mentioned above, more precise information after the tennis serve could mean to provide the exact location of the touchdown within the service box. A synonym for KR is 'information feedback' or 'reinforcement' (Schmidt & Lee 1999). The term reinforcement is basically correct as the augmented feedback indeed serves to reinforce future behaviour (e.g. minimizing the error). However, it contrasts with the previously mentioned 'reinforcement learning' and thereby may lead to misunderstandings. Precisely, we refer to the fact that the content of the information in reinforcement learning is limited (success versus failure) whereas the content of the information in the KR is extendible.

Dimensions of the augmented feedback

When applying augmented feedback to a learner, several aspects of the transfer of the information need to be considered. One of these aspects was discussed in the previous paragraph. Namely, it is of relevance if the augmented feedback is provided with respect to characteristics of the movement execution (knowledge of performance) or with respect to the final aim of the movement (KR). Besides that, there are several more aspects, which can be divided, according to their nature, in three groups. The first group (i) incorporates the aspect of the content of the information. The second group (ii) contains the aspect of the frequency of the augmented feedback, and the third group (iii) comprises the timing of the feedback relative to the movement execution. We will discuss these three in the following (see Figure 7.3).

Content of the information

The group content of the information considers the variable(s) 'extracted' from the movement and presented to the learner. For instance, it contains the question: which characteristics of the movement and/or of the final result of the movement are presented? Therefore, the distinction between knowledge of performance and KR belongs to this group.

A second aspect is the richness of the information. This aspect has been discussed above. A basketball player may be informed about whether or not the basket was hit. Alternatively, one may provide detailed information about the shot, e.g. that the distance error between ball and basket was 30 cm to the right and 15 cm up. In the literature, this difference has been termed qualitative versus quantitative feedback (Schmidt & Lee 1999). In the former, it is simply differentiated between success and failure. In the latter, additional information, e.g. about the size or the direction of the movement error, is provided.

Furthermore, the augmented feedback may comprise true or false information. For instance, when mentioning the visuomotor rotation paradigm, we discussed the possibility of altering the actual trajectory of the movement. Thus the content of the information is wrong. You may question why it could be reasonable to feed wrong information? One reason leads to basic research, specifically to the question how the nervous system acquires movements based on the integration of sensory information. Another reason is also related to basic science, namely how intrinsic feedback conflicts with augmented feedback in the process of learning.

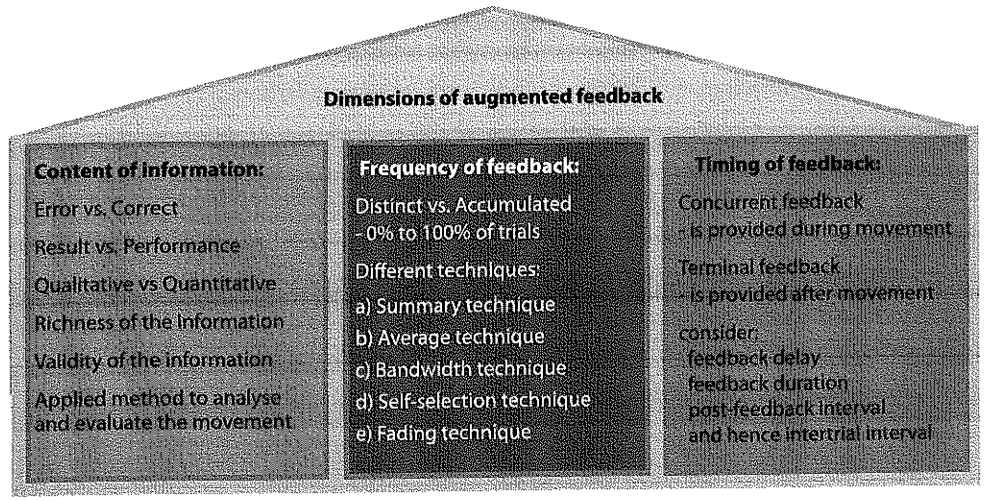

Figure 7.3 Dimensions of augmented feedback. When augmented feedback is conveyed to the learner, several aspects need to be considered. These aspects can be divided into three categories according to the nature of the information, namely (i) the content of the information, (ii) the frequency, and (iii) the timing of the feedback.

Apart from questions in basic research, applying wrong augmented feedback in a practical setting may be considered with caution. Previous experiments have indicated that augmented feedback may be superior to intrinsic feedback (see Magill 2001). A learner may therefore become hooked on augmented information and ignore the intrinsic feedback. A consequence would be the acquisition of wrong behaviour.

A last aspect we want to emphasize is the applied method to analyse the movement and convey the information. The information may be based on kinematic or kinetic analysis of the movement. For instance, one can present the elbow angle or the recorded counterforce when making a punching movement. Furthermore, physiological parameters could be used, such as the heart rate, blood pressure, muscle or brain activity measured with surface electromyography and electroencephalography. These physiological parameters have often been called 'biofeedback' in the literature. Finally, it is of relevance how the information is transported, e.g. by video, audio, or tactile sensation.

Frequency of the augmented feedback

The group 'frequency' is concerned with the question about how often a learner receives augmented feedback. This could be expressed as a percentage: 100 percent could thereby indicate that augmented feedback was provided in each of the executed movements and 0 percent would consequently mean that no feedback was provided at all. Besides the possibilities of providing feedback in each (or part) of the corresponding movements, several other techniques exist in the literature. Four of these techniques will be discussed: (a) the summary technique, (b) the average technique, (c) the bandwidth technique, and (d) the self-selection technique. For the (a) summary technique, the learner receives feedback after a defined number of trials for all of the executed movements performed so far. For instance, a tennis player may serve five times in a row and may then get the maximum velocity of the ball from each of the five services. A summary technique is especially suitable if there is a series of movements rapidly succeeding each other. The (b) average technique is similar to the summary technique. The difference with the average technique is that feedback is not presented from the performance of each of the previous trials but as a representative of all previous trials. In our example, the tennis player may receive the average of the maximum speed of the past five services. Consequently, this would be one value instead of five.

In the (c) bandwidth technique, a range is predefined where a movement is successful. For instance, in a tennis serve, it could be determined that the serve was successful when the ball hit somewhere within the opposite outer box. It is only if the tennis player misses the box that a distance error in the form of augmented feedback is provided (e.g. 1 m to the left and 50 cm behind the service box). You may argue that the learner receives feedback in any case – no matter if the error was in or out of the predefined range. This is certainly true, as subjects know that, when they do not receive feedback, the movement was correct and this is indeed a kind of feedback. The reason to use the bandwidth technique was argued to be the impossibility of correcting small errors of movement, especially in the early learning phase (see Magill 2001). When using the bandwidth technique only gross movement errors may be reported.

The last technique we will discuss is the (d) self-selection technique. Here, the learner decides himself/herself when he/she wants to receive feedback. The advantage of this technique is that the learner may pay heightened attention to the execution of the movement in order to judge when the movement was wrong and augmented feedback is required.

In particular, this last point may solve a potential problem also known as 'guidance hypothesis' (Schmidt & Lee 1999). As mentioned, augmented feedback is powerful and can therefore influentially guide the formation of new behaviour. The problem arises when the learner begins to depend solely on augmented feedback and loses confidence in the intrinsic perception. As a consequence, progress in learning can be hindered when augmented feedback is stopped.

Timing of the augmented feedback

The timing of the augmented feedback refers to the question of when, meaning in which phase of the movement, feedback is provided. There are two main ways to apply feedback. The first possibility is to provide feedback during movement execution. This is also called 'concurrent feedback'. The second possibility is to provide feedback after the movement is finished. This is often called 'terminal feedback'. A classical example of concurrent feedback is the monitoring of the heart rate while running. For the terminal feedback, two different aspects can be considered. The first aspect refers to the timing of the augmented feedback in relation to the end of the respective movement. In other words: it is concerned with the question how long one should wait to provide feedback after the movement is finished? The second aspect relates to the timing of the feedback with respect to the consecutive movement, essentially the point of how long one should wait for the execution of the subsequent movement after augmented feedback is provided.

With the discussion about the different dimensions of augmented feedback, we would like to finish the fundamental part of this chapter. So far, we mainly described basic facets of augmented feedback, starting with its definition, its use in the different processes of motor learning, and the different dimensions inherent in this subdivision of sensory feedback. In the following, we would like to apply this knowledge. Consequently, we will discuss the effect of augmented feedback in different areas, laboratory and field studies.

Augmented feedback can facilitate motor performance and learning

The acquisition of motor skills is fundamental to human life. The ability of a person to acquire with practice the proficiency to execute coordinated motor actions enables that person to have a wide range of human experiences. The experiences of motor skill learning may range from tying shoelaces, or relearning to walk after a stroke, to coping with a demanding surgical operation or acquiring a complex sport skill. It is widely known that task performance appears to improve in a consistent manner with practice (i.e. Fitts 1964, Adams 1987, Schmidt & Lee 1999, Magill 2001). It is, however, not just the amount of training, but also the training conditions and quality of practice that can have a significant effect on the rate of learning and final performance (e.g. Schmidt & Lee 1999).

One of the most critical variables affecting motor skill learning, aside from practice itself, is augmented feedback (Newell 1991). Augmented task-related feedback supplements the response-produced intrinsic feedback obtained from vision, audition, and proprioception. The learner can achieve a certain skill level with task-intrinsic feedback, but in order to attain a faster learning or a higher level of expertise, augmented feedback may indeed be beneficial (Magill 1994). In the tasks where the information from intrinsic sources does not provide the feedback needed to determine the appropriateness of the performance, or when the learner cannot adequately access the information critical to learning the skill, augmented feedback can play an essential role in effective skill acquisition (see Magill 1994).

Although it is a challenging task to optimize skill acquisition, it is also exceedingly important both theoretically in terms of understanding human learning and practically, for those seeking to devise training and rehabilitation paradigms, to enhance performance and/or improve quality of life (Green & Bavalier 2008). The use of augmented feedback (together with consideration of other learning determinants such as task difficulty, practice structure and motivation) does offer the potential to promote motor performance and learning.

Further evidence from lab and field studies on the role of augmented feedback

Ever since the beginning of the twentieth century and the seminal experiments of Thorndike (1927), augmented feedback has been considered critically important for learning motor skills, and research in motor skill learning has focused both on elucidating the mechanisms underlying reinforcement and feedback-mediated learning and on identifying key factors for optimization of learning. A variety of tasks and experimental paradigms have been used for studying motor skill learning and the effects of augmented feedback from basic lab experiments in animals and humans to learning in more ecological settings as in sports and clinical practice. Each of these approaches to motor learning offers different perspectives. Whereas studies of learning in sports, music and rehabilitation often yield knowledge relating to optimization of practice, the basic lab studies seek insights in the fundamental principles and mechanisms underlying learning and effects of augmented feedback.

With practice, there are improvements in performance that characterize skilled behaviour and these changes are accompanied by learning-dependent changes in the functional networks of the brain (for review see e.g. Seidler, 2010). Motor learning leads to behavioural changes that are implemented by processes that occur during practice as well as processes that evolve after practice ends. These processes and related network changes are thought to represent the formation of motor memory, which relates to encoding, consolidation and retrieval (Fuster 1995). The study of motor learning focuses on understanding the motor memory processes as well as practice-related factors that influence these memory processes. Learning mechanisms surely vary in their specific implementation across different domains, but some mechanisms and determinants of learning appear to be shared across domains. One of the most prominent practice-related determinants in motor learning is augmented feedback.

Augmented feedback can play different roles in the motor skill learning process (Schmidt & Lee 1999). First, augmented feedback may provide information about response errors and utility of reward via task-related information about the skill being performed or just performed. This information can be descriptive in whether the performance was successful or not, or more prescriptive in informing the learner about the errors made and/or what the learner should do to correct those errors. Whereas augmented feedback has long been believed to function primarily as reward, it can also be used to determine the nature of errors. This is critical in planning and correcting subsequent movements. Augmented feedback may in this sense also contribute to the development of accurate error detection and correction mechanisms through comparison of intrinsic internal and intrinsic external feedback (Young et al. 2001).

Second, augmented information feedback may motivate the learner by making the task seem more interesting and enjoyable, keep the learner alert and thereby lead learners to increase their efforts to achieve their learning goals (see Adams 1987, Little & McGullagh 1989, Annesi 1998, Silverman et al. 1998). As a result of motivation induced by augmented feedback, learners are inclined to strive longer, more frequently and with more effort (Schmidt & Lee 1999). Whereas motivation and arousal have been largely overlooked in the field of skill learning (see, however, Ackerman et al. 1995 and Ackerman & Cianciolo 2000) these factors are considered to be critically important components of most major theories of learning in other areas, e.g. social psychology and education (Green & Bavalier 2008). It is indeed logical that deliberate practice is an important variable for learning (Ericsson et al. 1993) and if augmented feedback increases it, it may certainly enhance learning. Recent studies do, however, also suggest a more direct motivational effect of augmented feedback on learning (Schmidt & Lee, 1999, Chiviacowski & Wulf 2007, Lewthwaite & Wulf 2010).

The heading of the present section states that augmented feedback can facilitate motor performance and learning. Although augmented feedback has repeatedly been demonstrated to facilitate changes in motor performance, it is important to emphasize the 'learning–performance distinction' (Salmoni et al. 1984, Schmidt & Lee 1999). Although performance and learning are inter-related, and we expect motor skill learning to be accompanied by an improved capability for motor performance, the essence of learning lies in its permanence over time (Kantak & Winstein 2012). The learning–performance distinction discriminates between the motor performance observed during practice and the resilience of this performance that develops during practice and is sustained over time (Cahill et al. 2001, Schmidt & Bjork 1992). In order to assess learning effects, motor performance should be measured not only during practice but also in retention tests at different time points following practice since this will reflect the efficiency of the memory processes evolved at that time (Kantak & Winstein 2012). Although augmented feedback may indeed facilitate motor performance during practice, retention tests are consequently necessary in order to assess the potential beneficial effects of augmented feedback on learning.

Although performance and acquisition are two distinct phenomena, they are intricately linked. It has been demonstrated that subjects who practise a motor task in a reduced feedback condition perform better in a delayed retention test compared to subjects who practise with augmented feedback during or following every practice trial (Schmidt et al. 1989, Sherwood 1998, Winstein & Schmidt 1990, Guay et al. 1999, Anderson et al. 2005). Although a poor performance in certain practice setting may ultimately lead to better retention, this may not

be appreciated very well by the learner, the trainer or the therapist who wish to experience excellence in performance during practice (Lee & Wishart 2005). Consequently, it is a major challenge to structure practice sessions that may motivate the learner, enhance performance as well as maximize retention in delayed tests.

While augmented feedback may indeed enhance motor performance and learning (Lee et al. 1995, Swinnen et al. 1997, Swinnen 2002, Puttemans et al. 2005) the optimal implementation of augmented feedback is not straightforward and there may be potential pitfalls depending on the specific task and learner characteristics (Magill 1994). First, performance changes do occur in the absence of augmented feedback indicating a role of error detection and correction processes for the learning. It is critical that augmented feedback aids these processes and does not replace them. Second, when augmented feedback does facilitate learning, the learner does not require it on every trial. Third, in some instances augmented feedback may even be detrimental to learning effects observed in delayed tests (Swinnen 1996). In recent decades extensive evidence from behavioural studies has suggested that providing augmented feedback during training improves performance, whereas its removal during subsequent retention tests or conditions may result in performance deterioration. This has come to be known as the 'feedback-guidance hypothesis' (see above), suggesting that availability of augmented feedback during training guides the learner towards proper motor output, but its subsequent removal may lead to performance decrements and/or suboptimal retention (Salmoni et al. 1983, Schmidt et al. 1989, 1990, Winstein and Schmidt 1990, Swinnen 1996). This is presumably a consequence of the learner becoming too dependent on augmented feedback, possibly at the expense of relying on the intrinsic feedback to support performance under nonaugmented test conditions (Salmoni et al. 1984, Swinnen 1996, Schmidt and Lee 1999, Magill 2007). Recently, Ronsse et al. (2011) provided evidence on the neural basis of the feedback-guidance hypothesis by the use of fMRI. Whereas frequent feedback may guide the learner to a correct response during practice and interfere with or replace active problem-solving processes, reduced feedback practice conditions are hypothesized to increase information-processing demands during practice that are advantageous to the relatively permanent motor learning effects observed in delayed retention tests (Sullivan et al. 2008). In order to implement augmented feedback in an optimal way and diminish feedback-dependency effects, it is consequently necessary to carefully consider the specific learner and task characteristics when designing skill learning paradigms (Magill 1994, Swinnen 1996).

The exact role that augmented feedback plays in learning is still a subject of much debate within the field. Numerous examples have demonstrated that feedback is necessary for learning, whereas other counterexamples have not been able to demonstrate a necessity of augmented feedback for learning. A complication is that learning may relate to reward-prediction errors and even when experimenter-generated augmented feedback is not provided, participants will nevertheless have varying degrees of confidence that their performance was correct, which could act as a de facto feedback signal (Mollon & Danilova 1996, Green & Bavalier 2008). Interestingly, learners often have an accurate impression of how they perform. Recent studies have shown beneficial learning and retention effects of providing augmented feedback following 'good' trials (throwing to a target) compared to 'poor' trials (Chiviacowski & Wulf 2007), and further studies have demonstrated enhanced motor learning by providing (false) positive relative to negative normative feedback (Wulf et al. 2010a, Wulf & Lewthwaite 2010, Lewthwaite & Wulf 2010). In one study, two groups of subjects practised a balance task. In addition to receiving veridical feedback on their performance after each trial, subjects also received normative feedback if they were better or worse than average. The 'better' group were led to believe that their performance was better than average, whereas the opposite was the case for the 'worse' group. In transfer tests, the 'better' group demonstrated more effective learning than the 'worse' group (Wulf & Lewthwaite 2010) and this was also the case in another study where the 'better' group was compared to controls who received only veridical feedback (Lewthwaite & Wulf 2010). Thus, the mere conviction of being 'good' enhances learning and feedback cannot merely be viewed as information, which is processed without affective connotation. On the contrary, the valence of feedback can indeed enhance learning (Wulf et al. 2010b).

Essentially, the principal question is not whether augmented feedback is necessary, but if augmented feedback may be beneficial for learning and if so, how is it best implemented in order to promote learning. In all likelihood, the importance of augmented feedback for motor skill learning depends heavily on the characteristics of the specific skill or task and the learner, and this may indeed explain the seemingly inconsistent findings of different studies.

Considering the characteristics of the task and the learner, Newell (1974) demonstrated how important augmented feedback is in a situation in which the intrinsic feedback needed to perform a skill is not available or the learner is not yet capable of using it. Subjects had to make a specific lever movement in 150 ms. Although they could see their arm, the lever and the target, their success in learning the task depended on how many times they had received KR about their performance. The results indicated that in the early learning phase the learner did not have a good internal model for the movement. They needed KR for more than 50 trials to establish this, and by then the movement could be performed without augmented feedback (Newell 1974). Different tasks also have different requirements and hence also different implications for augmented feedback. The role of augmented feedback in motor learning has been investigated for a wide range of tasks and skills from simple tasks with single degree of freedom movements in isolated lab experiments to complicated coordination tasks in more complex ecological settings.

Fowler and Turvey (1978) suggested that the required information content of the provided feedback must contain as many degrees of constraint as there are degrees of freedom in the action to be coordinated. In simple motor skills with single degree of freedom, or in practice of complex tasks where the focus is specifically on single parameters or the scaling of a given coordination pattern, KR usually specifies all the information that is needed for learning, e.g. in a ballistic task (see Salmoni et al. 1984, Newell 1974; see Swinnen 1996, for a review). Lavery (1962) found beneficial effects of KR in a simple ballistic task, where a ball had to be propelled to a target, and this finding has beem replicated by many studies. In a recent study we also found ballistic motor learning in a single-joint task to be highly enhanced by KR (Lundbye-Jensen et al. 2012). Relating to ballistic learning but in a more functional setting, Moran et al. (2011) investigated practice of service speed in tennis and found that KR is needed in order for players to improve with practice. This finding does indeed make sense since the learners do not acquire a new coordination pattern, but focus on improving a single parameter in a pre-existing skill. KR may, in other words, have a sufficiently prescriptive function in simple tasks. In addition to a beneficial role of KR, Lavery (1962) also demonstrated beneficial effects of summary KR relative to single-trial KR and this effect was also found and extended in more recent studies (e.g. Guadagnoli et al. 1996; Schmidt et al. 1989, 1990; Yao et al. 1994). The optimal frequency of augmented feedback does indeed interact with task complexity in affecting motor skill learning, and there is some evidence that the learning of simple motor tasks may benefit from a reduction in augmented feedback (Winstein & Schmidt 1990, Lai & Shea 1999). One explanation for this could be that when the task and the performance measure are isomorphic, as often happens in simple tasks, learners do not need augmented feedback on every trial (Magill 1994). Learning of a simple task might also be enhanced by a reduced feedback frequency, because withholding feedback makes practice

more difficult or challenging, and it forces the learner to develop his or her own internal error detection and correction mechanisms (Wulf & Shea 2002).

While learning of simple skills may benefit from KR and reducing or delaying the augmented feedback, the usefulness of KR to a learner in acquiring wholebody actions or complex skills where the learner needs to establish new coordination modes has been questioned for a long time (Newell 1991, Gentile 1972). There is indeed evidence to suggest that different and more frequent feedback can be beneficial for the learning of more complex skills (Schmidt et al. 1990, Yao et al. 1994, Guadagnoli et al. 1996, Wulf & Shea 2002). Wulf and Shea (2002) proposed that because complex tasks require different components to be coordinated in order to produce skilled performance, the learner also has to rely on intrinsic feedback, and augmented feedback is generally not as prescriptive as in simple tasks. In complex tasks, the learner presumably benefits from information about the dynamics of the recent task performance in addition to the KR (Newell 1991), and KP describing movement kinematics or kinetics has been demonstrated to be more important than KR alone in complex skill learning (e.g. Newell & Walter 1981, Newell & Carlton 1987, Schmidt & Lee 1999).

In complex skill learning, augmented feedback may be given based on multiple different performance characteristics and learning inherently involves higher demands on control, error-detection and problem-solving. Based on this, the learning processes may not benefit from increasing the demands imposed on the learner further as it has been seen for simple tasks, e.g. by reducing feedback frequency (see Wulf & Shea 2002). On the contrary, learning may be enhanced by more frequent feedback (Magill 1994, Wulf & Shea 2004). Guadagnoli et al. (1996) directly demonstrated that task complexity and task-related experience interacted with the optimal number of trials summarized in the augmented feedback. Whereas reduced feedback frequencies benefited the learning of a simple striking task for novice and experienced participants, frequent (single-trial) feedback was more effective than longer feedback summaries in the learning of a more complex double-striking task, particularly for novices.

Several studies have replicated the finding that frequent (100 percent) feedback can be beneficial in complex skill learning, e.g. involving bimanual coordination (Swinnen et al. 1997, Wulf & Shea 2002) and, although frequent visual feedback typically promotes strong feedback dependency (at least for simple skills), this was not found to the same extent for these more complex tasks. It may be that this reduced susceptibility to feedback dependency in complex learning relates to a different role of intrinsic feedback (Wulf & Shea 2004). With regard to complex motor tasks, a number of studies have found that the performance and learning of a skill, such as dance routines (Clarkson et al. 1986), cycling (Sanderson & Cavanagh 1990, Broker et al. 1993), and swimming (Chollet et al. 1988), is enhanced when concurrent feedback is provided. These studies indicate that augmented feedback in real time can have a powerful effect on performance in certain sport tasks. Additionally, the added use of kinematic and kinetic information feedback facilitates motor learning beyond the level reached by presentation of KR alone (Newell 1991). Kinematic feedback has been demonstrated to be beneficial for learning a golf shot and increasing power output in a leg press exercise (Hopper et al. 2003). The effectiveness of kinematic feedback does, however, depend on the relevance of the feedback to the success of the movement or task goal. Furthermore, many studies of kinematic feedback have not obtained results in delayed retention or transfer tests.

Augmented feedback, properly employed, may also have practical implications for rehabilitation therapy since the re-acquisition of motor skills is an important part of functional motor recovery (Winstein 1991). An important question for physiotherapists working in rehabilitation is whether the research findings for healthy subjects apply to patients, e.g.

persons with stroke. This depends on whether people with stroke learn in the same way as people with an intact nervous system and whether the tasks which are practised in rehabilitation are comparable to the tasks investigated in research studies (van Vliet & Wulf 2006). Concerning the second question, a rehabilitation professional may find it challenging to implement principles derived from studies of laboratory-based tasks since these findings may not generalize into a clinical setting.

Concerning the first question, the principles of learning and the factors influencing learning are to a large extent identical between groups, but there may indeed be differences in learning ability, strategy etc. between individuals and groups of patients. Some patients may have a compromised ability to process intrinsic feedback due to neurological sensory impairments and some patients with cognitive and perceptual impairments may not be able to use intrinsic feedback to guide their performance. These factors may indeed influence the role of augmented feedback in learning and consequently also have implications for how augmented feedback should be provided.

There are indications that addition of augmented feedback to exercises can stimulate the learning process in rehabilitation therapy by making patients more aware of their performance (Holden 2005, Winstein & Stewart 2006) and systematic reviews indicate that augmented feedback in general has an added value for e.g. stroke rehabilitation. Molier et al. (2010) found trends in favour of providing augmented KP, augmented auditory feedback and combined sensory and visual feedback. There were no consistent effects on motor relearning for summary or faded, terminal or concurrent, solely visual or solely somatosensory augmented feedback. Although augmented feedback may be beneficial in rehabilitation, it is difficult to identify patients or groups of patients who might be more likely to benefit from a specific type of intervention due to heterogeneity of patients, groups and conducted trials, and Van Dijk et al. (2005) found no general differences in effectiveness between different therapeutic interventions using augmented feedback, i.e. electromyographic biofeedback, kinetic feedback, kinematic feedback, and KR.

Augmented feedback may indeed be beneficial for the reacquisition of motor skills in rehabilitation. Winstein (1991) suggested that it is appropriate to use the principles obtained through laboratory experimentation as guidelines rather than as exact recommendations when applying basic research findings to clinical practice. It is, however, not yet possible to formulate to what extent principles of augmented feedback are properly employed (van Dijk et al. 2005). Future studies should focus more on the content, form, and timing of augmented feedback in the therapeutic interventions and importantly distinguish performance and learning effects by assessing learning in delayed retention tests. Additionally, it is important to incorporate considerations about the role of the specific characteristics of the individual learner or patient (Magill 1994).

Individual differences in the benefits of feedback for learning

As discussed previously, different skills and tasks have different characteristics and learners are also different. From a motor skill acquisition point of view learners have individual differences in motor experience and baseline task performance, which will most likely influence skill acquisition (Magill 1994). Additionally, learning requires the use of cognitive resources and effort during practice. While advantageous for some people, the demands of a task may exceed the optimal capability for other individuals, especially those with reduced or impaired information-processing abilities (Sullivan et al. 2008, Kelley & McLaughlin 2012).

The amount of cognitive resources that learners possess is positively related to learning. Learners with more cognitive resources and higher abilities related to the task, learn faster than those lower in those abilities (Craik & Salthouse, 2000; Engle & Kane, 2004). The

advantage for learners with higher resources may be explained through cognitive load theory (Kelley & McLaughlin 2012). Guadagnoli and Lee (2004) have proposed a framework which suggests that motor learning depends on the level of challenge emerging from an interaction of the information-processing capability of the learner, task demands, and practice condition. According to this framework, there is a point of optimal challenge that yields maximum practice benefits when optimal cognitive effort is invoked. A level of challenge below or above this optimal challenge point may attenuate learning. That is, conditions that demand too much cognitive effort may interfere with learning effects (Sullivan et al. 2008). One way to ensure that the demands of the task are optimally aligned to the resources at hand is to modify the task demands and/or to provide adjusted augmented feedback. In a recent study, Kelley & McLaughlin (2012) found positive interactions between individual differences in cognitive resources and adjusted augmented feedback during the process of learning. Those with higher abilities for the type of demands imposed by the task were more likely to benefit from reduced feedback.

Based on the discussion in the preceeding paragraphs, we suggest the following considerations for feedback design: Incorporate learner characteristics and task demands when designing learning support via augmented feedback (Magill 1994). Optimal feedback characteristics depend on individual differences in the learners' ability levels for the demands of the task being learned (Kelley and McLaughlin 2012). This is of outmost importance not only in skill learning relating to sports and daily activities but even more so in clinical practice.

Subliminal augmented feedback and motor learning

Augmented feedback may not only have an effect when it is consciously perceived by the learner. During daily life the central nervous system constantly receives and processes sensory input providing information on the state of our body and the surrounding world. Although we do not consciously perceive all sensory inputs, these may nevertheless have consequences for our future behaviour. Although evidence of subconscious processing has been debated for several decades, and the literature is not free of controversy, it is a well-described phenomenon that we may respond to features of our surroundings without being aware of them (e.g. Goodale et al. 1991, Goodale & Milner 1992, Pessiglione et al. 2007, Goodale 2008).

Subliminal stimuli may be presented to subjects as auditory stimuli, e.g. as tones with frequencies outside the perceptible range, at extremely low intensities or in some scrambled form. They may also be presented visually as low-contrast images presented for very brief durations or masked by other figures. In addition to these modalities, subliminal cues may also be presented as e.g. augmented sensory feedback, e.g. induced by tactile stimulation, vibration etc.

Several studies have demonstrated correct reactions in spite of conscious visual perception being disrupted through temporary knock-out of the visual cortex (Amassian et al. 1989, Christensen et al. 2008), and basic research studies manipulating only the augmented feedback characteristics have also provided evidence for processing of subliminal cues leading to behavioural changes. Eimer & Schlaghecken (2003) observed changes in reaction times and Taylor & McCloskey (1996) observed behavioural changes in a choice reaction task based on subliminal visual information. In recent studies it has also been observed that subliminal vibrotactile stimulation can lead to increased postural stability and balance in young and elderly subjects and in diabetes and stroke patients. Furthermore this subliminal stimulation can also reduce gait variability in elderly fallers (Galica et al. 2009, Priplata et al. 2002, Priplata et al. 2003).

Since learning may be reinforced by augmented feedback, and subliminal stimuli, which are not consciously perceived, may affect behavior, it may indeed be hypothesized that learning could also be facilitated by subliminal augmented feedback on motor performance. Pessiglione et al. (2006) demonstrated that modulation of dopamine-dependent striatal activity during learning can account for how the human brain uses reward prediction errors to improve future decisions, and Pessiglione et al. (2007) also used functional magnetic resonance imaging to investigate the neural basis of processing subliminal stimuli and the translation to behaviour. The study focused on an incentive force task and used money as reward, which was presented either subliminally or for a longer time leading to a conscious perception of the stimulus. Even when subjects could not report how much money was at stake, they nevertheless deployed more force for higher amounts. The findings imply that expected rewards may indeed energize behaviour, without the need for the subjects' awareness. This indicates that motivational processes involved in boosting behaviour are qualitatively similar, despite whether subjects are conscious or not of the reward at stake. Consistently, the same basal forebrain region underpinned subliminal and conscious motivation.

While there have been some positive results (e.g. Masters et al. 2009), motor skill learning based on subliminal augmented feedback has not yet been consistently demonstrated. It is, however, a very interesting area. Pessiglione et al. (2007) focused on motivation, rather than motor learning, but the results are consistent with the notion (and our recent observation) that subliminal augmented feedback can also facilitate motor learning (Lundbye-Jensen et al. 2012). As it may be beneficial to combine augmented feedback modalities in motor learning, it may also potentially be beneficial for learning to combine supraliminal and subliminal augmented feedback.

Conclusions and perspectives

As we have seen in this chapter, augmented feedback may be very powerful to facilitate performance. This type of feedback can be applied in a variety of motor learning processes and in a variety of ways. Regarding the possible ways, we mentioned and discussed three dimensions. The 'content of the information' considers the variable(s) 'extracted' from the movement and presented to the learner. The 'frequency of the augmented feedback' comprises the aspect of the number of instances of feedback in relation to the number of executed movements. Finally, the group 'timing of the feedback' is concerned with the timing of the feedback relative to the phase of the movement.

From our point of view, the power of the augmented feedback to facilitate performance in learning is of great interest for both, scientific research as well as for the praxis. Regarding its power, we have already mentioned the fact (and the potential risk) that learners may become hooked on augmented feedback and even lose trust in their internal sensation(s). Consequently, augmented feedback may be optimally applied in a practical setting such as motor rehabilitation or in the early phase of learning where external and explicit guiding is significant. This guiding may be necessary because of uncertainties in the internal sensation after injuries or diseases and/or because of non-existing experiences (referring to either the movement per se or the external world with which the person has to interact).

However, we argue that, to reasonably apply augmented feedback in these settings, important future work needs to be done. We specifically relate this future work to the efficiency of the outcome when learning with augmented feedback. For instance, consider a sensorimotor training in the rehabilitation after a stroke. What would you recommend as the content of the information provided in the form of augmented feedback? What should be the frequency of the information relative to the executed movement and what should be the timing of the

feedback to maximize its effect? You do not know? Neither do we. In our opinion, these questions require substantial research work to clarify in which setting augmented feedback should be applied in which form, how often, when, and furthermore how individual characteristics should be accounted for. Practically, these evaluations would need to be done in two steps. In the first step, laboratory work is required. In the second step, the acquired knowledge would need to be tested in practical (real world) settings. This is important as the implementation finally takes place in praxis and not in the laboratory.

A last thing we want to focus on is the combination of supraliminal and subliminal augmented feedback. We have already mentioned that, in addition to augmented feedback consciously perceived by the learner, subconscious (subliminal) information is processed in the central nervous system. Not only is it processed but it may also facilitate performance in motor learning. Therefore, it would be interesting to know whether the combination of supraliminal augmented feedback and subliminal augmented feedback can facilitate performance to a greater extent than each of these alone. A rationale for an enhanced facilitation may be the postulated processing of the information, specifically the notion that supraliminal and subliminal information is differently processed (presumably relating to the involved pathways) in the central nervous system.

At this point we want to end the chapter. We hope that we have made clear the definition of augmented feedback and its influence in motor learning. Furthermore, we hope that we have made clear its important capability, when appropriately adjusted, to facilitate motor performance and promote learning processes.

References

Ackerman, P.L., Kanfer, R. & Goff, M. (1995) Cognitive and noncognitive determinants and consequences of complex skill acquisition. J. Exp. Psychol: Applied 1: 270–304

Ackerman, P.L. & Cianciolo, A.T. (2000) Cognitive perceptual-speed, and psychomotor determinants of individual differences during skill acquisition. J. Exp. Psychol: Applied 6: 259–290. PMID: 11218338.

Adams, J.A. (1987) Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. Psychol. Bull. 101:41–74

Amassian, V.E., Cracco, R.Q., Maccabee, P.J., Cracco, J.B., Rudell, A., Eberle, L. (1989) Suppression of visual perception by magnetic coil stimulation of human occipital cortex. Electroencephalogr. Clin.Neurophysiol. 74:458–462

Anderson, D.I., Magill, R.A., Sekiya, H., Ryan, G. (2005) Support for an explanation of the guidance effect in motor skill learning. J. Mot. Behav. 2005;37:231–238

Annesi, J. J. (1998) Effects of computer feedback on adherence to exercise. Percept. Motor Skills 87: 723–730

Bernstein, N.A. (1967) The co-ordination and regulation of movements. Pergamon Press, Oxford

Broker, J.P., Gregor, R.J. & Schmidt, R.A. (1993) Extrinsic feedback and the learning of kinetic patterns in cycling. J. Appl. Biomech. 9: 111–123

Cahill, L., McGaugh, J.L., Weinberger, N.M. (2001) The neurobiology of learning and memory: some reminders to remember. Trends Neurosci. 24:578–581

Christensen, M.S., Kristiansen, L., Rowe, J.B., Nielsen, J.B. (2008) Action-blindsight in healthy subjects after transcranial magnetic stimulation. Proc. Natl. Acad. Sci. USA 105:1353–1357

Chiviacowski, S. & Wulf, G. (2007) Feedback after good trials enhances learning. Res. Qu. Exerc. Sport, 78: 40–47

Chollet, D., Micallef, J.P. & Rabischong, P. (1988) Biomechanical signals for external biofeedback to improve swimming techniques. In B. E. Ungerechts, K. Wilke & K. Reischle (eds.) Swimming V. Champaign, IL: Human Kinetics, 389–396

Clarkson, P.M., James, R., Watkins, A. & Foley, P. (1986) The effect of augmented feedback on foot pronation during barre exercise in dance. Res. Qu. Exerc. Sport 57: 33–40

Craik, F. & Salthouse, T.A. (eds) (2000) The Handbook of Aging and Cognition. Mahwah, NJ: Lawrence Erlbaum.
Eimer, M. & Schlaghecken, F. (2003) Response facilitation and inhibition in subliminal priming. Biol. Psychol. 64:7–26
Engle, R.W. & Kane, M.J. (2004) Executive attention, Worning memory capacity, and a two-factor theory of cognitive control. Psychol. Learn. Motiv., 44, 145–198.
Ernst, M.O. & Banks, M.S. (2002) Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415:429–433
Ericsson, K.A., Krampe, R.Th. & Tesch-Römer, C. (1993) The role of deliberate practice in the acquisition of expert performance. Psychol. Rev., 100(3): 363–406
Faisal, A.A., Selen, L.P., Wolpert, D.M. (2008) Noise in the nervous system. Nat. Rev. Neurosci. 9:292–303
Fitts, P.M. (1964) Perceptual-motor skill learning. In A.W. Melton (ed.) Categories of human learning. New York: Academic Press, 243–285
Fowler, C.A. & Turvey, M.T. (1978) Skill acquisition: an event approach with special reference to searching for the optimum of a function of several variables. In G.E. Stelmach (ed.) Information processing in motor control and learning. New York: Academic Press, 1–40
Fuster, J.M. (1995) Memory in the cerebral cortex: an empirical approach to neural networks in the human and nonhuman primate. Cambridge, MA: MIT Press
Galica, A.M., Kang, H.G., Priplata, A.A., D'Andrea, S.E., Starobinets, O.V., Sorond, F.A., Cupples, L.A., Lipsitz, L.A. (2009) Subsensory vibrations to the feet reduce gait variability in elderly fallers. Gait Posture 30(3):383–387
Gentile, A.M. (1972) A working model of skill acquisition with application to teaching. Quest 17: 3–23
Goodale, M.A., Milner, A.D., Jakobson, L.S., Carey, D.P. (1991) A neurological dissociation between perceiving objects and grasping them. Nature 349:154–156
Goodale, M.A. & Milner, A.D. (1992) Separate visual pathways for perception and action. Trends Neurosci. 15: 20–25
Goodale, M.A. (2008) Action without perception in human vision, Cogn. Neuropsychol. 25:7:891–919
Green, C.S. & Bavalier, D. (2008) Exercising Your Brain: A review of human brain plasticity and training-induced learning. Psychol Aging. December; 23(4): 692–701. doi:10.1037/a0014345
Guadagnoli, M.A., Dornier, L.A. & Tandy, R. (1996) Optimal length for summary of results: the influence of task related experience and complexity. Res. Qu. Exerc. Sport 67: 239–348
Guadagnoli, M.A. & Lee, T.D. (2004) Challenge point: a framework for conceptualizing the effects of various practice conditions in mo- tor learning. J. Mot. Behav. 36: 212–224
Guay, M., Salmoni, A., Lajoie, Y. (1999) The effects of different knowledge of results spacing and summarizing techniques on the acquisition of a ballistic movement. Res. Q. Exerc. Sport. 70:24–32
Holden, M.K. (2005) Virtual environments for motor rehabilitation: review, Cyberpsychol. Behav. June:8(3):187–211; discussion 212–19
Hopper, D., Berg, M., Andersen, H. and Madan, R. (2003) The influence of visual feedback on power during leg press on elite women field hockey players, Phys. Ther. Sport 4: 182–186
Kantak, S.S., Winstein, C.J. (2012) Learning–performance distinction and memory processes for motor skills: A focused review and perspective. Behav. Brain Res. March 1; 228 (1): 219–231, doi: 10.1016/ j.bbr.2011.11.028
Kelley, C.M. & McLaughlin, A.C. (2012) Individual differences in the benefits of feedback for learning. In Human Factors: J. Human Factors and Ergonomics Society 54: 26.
Krakauer, J.W. (2009) Motor learning and consolidation: the case of visuomotor rotation. Adv. Exp. Med. & Biol. 629:405–421. doi: 10.1007/978-0-387-77064-2_21
Lai, Q. & Shea, C.H. (1999) The role of reduced frequency of knowledge of results during practice. Res. Qu. Exerc. Sport 70: 33–40
Lavery, J.J. (1962) Retention of simple motor skills as a function of type of knowledge of results. Can. J. Psychol. 16: 300–311
Lee, T., Swinnen, S., Verschueren, S. (1995) Relative phase alterations. during bimanual skill acquisition. J. Mot. Behav. 27:263–274
Lee, T.D. & Wishart, L.R. (2005) Motor learning conundrums (and possible solutions). Quest 57:67–78
Lewthwaite, R. & Wulf, G. (2010) Social-comparative feedback affects motor skill learning. Qu. J. Exp. Psychol., 63: 738–749

Little, W.S. & McGullagh, P. (1989) Motivation orientation and modelled instruction strategies: The effects of form and accuracy. J. Sport Exerc. Psychol. 11: 41–53
Lundbye-Jensen, J., Petersen, T.H., Rothwell, J.C., Nielsen, J.B. (2011) Interference in ballistic motor learning: Specificity and role of sensory error signals. PloS One March 9; 6(3): e17451, pp. 1–15, doi: 10.1371/journal.pone.0017451
Lundbye-Jensen, J., Leukel, C. & Nielsen, J.B. (2012) Learning without knowing: subliminal visual feedback facilitates motor learning. Manuscript submitted for publication
Magill, R.A. (1994) The influence of augmented feedback on skill learning depends on characteristics of the skill and the learner. Quest 46: 314–327
Magill, R.A. (2001) Augmented feedback in motor skill acquisition. In R.N. Singer, H.A. Hausenblas and C.M. Janelle (eds) Handbook of sport psychology. New York: John Wiley & Sons
Magill, R.A. (2007) Motor learning and control: concepts and applications. 8th edn. New York: McGraw-Hill
Marchese, R., Diverio, M., Zucchi, F., Lentino, C. & Abbruzzese, G. (2000) The role of sensory cues in the rehabilitation of Parkinsonian patients: a comparison of two physical therapy protocols. Mov. Disord., 15(5), 879–883
Masters, R.S.W., Maxwell, J.P. & Eves, F.F. (2009) Marginally perceptible outcome feedback, motor learning and implicit processes. Conscious. Cogn. 18: 639–645
Mollon, J.D. & Danilova, M.V. (1996) Three remarks on perceptual learning. Spat. Vis. 10(1): 51–58
Molier, B.I., van Asseldonk, E.H.F., Hermens, H.J., Jannink, M.J.A. (2010) Nature, timing, frequency, and type of augmented feedback; does it influence motor relearning of the hemiparetic arm after stroke? A systematic review. Disabil. Rehab.: 32(22): 1799–1809
Moran, K., Kieran, A., Murphy, C. & Marshall, B. (2011) The need and benefit of augmented feedback on service speed in tennis. Med. Sci. Sports Exerc.: April: 44(4): 754–760
Newell, K.M. (1974) Knowledge of result and motor learning. J. Mot. Behav. 6: 235–244
Newell, K.M. & Walter, C.B. (1981) Kinematic and kinetic parameters as information feedback in motor skill acquisition. J. Hum. Mov. Stud. 7, 235–254
Newell, K.M. & Carlton, M.J. (1987) Augmented information feedback and the acquisition of isometric tasks. J. Mot. Behav. 19: 4–12
Newell, K.M. (1991) Motor skill acquisition. Ann. Rev. Psychol. 42: 213–237
Pessiglione, M., Schmidt, L., Draganski, B., Kalisch, R., Lau, H., Dolan, R.J. and Frith, C.D. (2007) How the brain translates money into force: A neuroimaging study of subliminal motivation. Science. May 11: 316(5826): 904–906
Pessiglione, M., Seymour, B., Flandin, G., Dolan, R.J. & Frith, C.D. (2006) Dopamine-dependent prediction errors underpin reward-seeking behaviour in humans. Nature 442: 1042–1045
Priplata, A., Niemi, J., Salen, M., Harry, J. & Lipsitz, L. (2002) Noise-enhanced human balance control. Phys. Rev. Lett. 3–6
Priplata, A., Niemi, J., Harry, J. & Lipsitz, L. (2003) Vibrating insoles and balance control in elderly people. The Lancet 362: 1123–1124
Puttemans, V., Wenderoth, N., Swinnen, S.P. (2005) Changes in brain activation during the acquisition of a multifrequency bimanual coordination task: from the cognitive stage to advanced levels of automaticity. J. Neurosci. 25:4270–4278
Ronsse, R., Puttemans, V., Coxon, J.P., Goble, D.J., Wagemans, J., Wenderoth, N. & Swinnen, S.P. (2011) Motor learning with augmented feedback: modality-dependent behavioral and neural consequences. Cereb. Cortex June: 21:1283–1294
Salmoni, A.W., Schmidt, R.A., Walter, C.B. (1984) Knowledge of results and motor learning: a review and critical reappraisal. Psychol. Bull. 1984;95:355–86
Salmoni, A.W., Ross, D., Dillb, S., Zoellerb, M. (1983) Knowledge of results and perceptual-motor learning. Hum. Mov. Sci. 2:77–89
Sanderson, D.J. & Cavanagh, P.R. (1990) Use of augmented feedback for the modification of the pedaling mechanics of cyclists. Can. J. Sport Sci. 15: 38–42
Schmidt, R.A., Lange, C., Young, D.E. (1990) Optimizing summary knowledge of results for skill learning. Hum. Mov. Sci. 9:325–348
Schmidt, R.A., Young, D.E., Swinnen, S., Shapiro, D.C. (1989) Summary knowledge of results for skill acquisition: support for the guidance hypothesis. J. Exp. Psychol. Learn. Mem. Cogn. 15:352–359
Schmidt, R.A. & Bjork, R.A. (1992) New conceptualization of practice: common principles in three paradigms suggest new concepts for training. Psychol. Sci. 1992;3:207–217

Schmidt, R.A. & Lee, T.D. (1999) Human control and learning: A behavioral emphasis. Champaign, IL: Human Kinetics

Seidler, R.D. (2010) Neural correlates of motor learning, transfer of learning, and learning to learn. Exerc. Sport Sci. Rev., 38(1): 3–9

Sherwood, D.E. (1988) Effect of bandwidth knowledge of results on movement consistency. Percept. Mot. Skills. 66:535–542

Silverman, S. S., Woods, A. M. & Subramaniam, P. R. (1998) Task structures, feedback to individual students, and student skill level in physical education. Res. Qu. Exerc. Sport 69, 420–424

Sullivan, K.J., Kantak, S.S., Burtner, P.A. (2008) Motor learning in children: Feedback effects on skill acquisition. Phys. Ther. 88:720–732

Swinnen, S. P. (1996) Information feedback for motor skill learning: A review. In N. Zelaznik (ed.) Advances in motor learning and control. Champaign, IL: Human Kinetics, 37–66

Swinnen, S.P., Lee, T.D., Verschueren, S., Serrien, D.J., Bogaerds, H. (1997) Interlimb coordination: learning and transfer under different feedback conditions. Hum. Mov. Sci. 16:749–785

Swinnen, S.P. (2002) Intermanual coordination: from behavioural principles to neural-network interactions. Nat. Rev. Neurosci. 3:348–359

Taylor, J.L. & McCloskey, D.I. (1996) Selection of motor responses on the basis of unperceived stimuli. Exp. Brain Res. 110:62–66

Thorndike, E.L. (1927) The law of effect. Am. J. Psychol., 39, 212–22

van Dijk, H., Jannink, M.J.A. & Hermens, H.J. (2005) Effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients: a systematic review of randomized controlled trials. J. Rehab. Med. 2005, 37(4), 202–211

van Vliet P.M. & Wulf G. (2006) Extrinsic feedback for motor learning after stroke: what is the evidence? Disabil. Rehabil. July: 28(13–14):831–40

Winstein, C.J. & Schmidt, R.A. (1990) Reduced frequency of knowledge of results enhances motor skill learning. J. Exp. Psychol. Learn. Mem. Cogn. 1990;16:677–691

Winstein, C.J. (1991) Knowledge of results and motor learning–implications for physical therapy. Phys. Ther. 71:140–149

Winstein, C.J. & Stewart, J.C. (2006) Textbook of neural repair and rehabilitation. Volume 2, Medical neurorehabilitation. Cambridge: Cambridge University Press, 89–102

Wolpert, D.M., Diedrichsen, J., Flanagan, J.R. (2011) Principles of sensorimotor learning. Nature reviews. Neuroscience 12:739–751 doi: 10.1038/nrn3112

Wolpert, D.M. & Ghahramani, Z. (2000) Computational principles of movement neuroscience. Nat. Neurosci. 3 Suppl:1212–1217

Wulf, G. & Shea, C. (2002) Principles derived from the study of simple skills do not generalize to complex skill learning. Psychonom. Bull. Rev. 9, 185–211

Wulf, G. & Shea, C.H. (2004) Understanding the role of augmented feedback: The good, the bad, and the ugly. In A.M. Williams, & N.J. Hodges (eds.), Skill acquisition in sport: Research, theory and practice (pp. 121–44). London: Routledge

Wulf, G., Chiviacowsky, S., Lewthwaite, R. (2010a) Normative feedback effects on the learning of a timing task. Res. Q. Exerc. Sport Dec.:81(4):425–31

Wulf, G. & Lewthwaite, R. (2010) Social-comparison feedback and conceptions of ability: effects on motor learning. Q. J. Exp. Psychol. (Hove). Apr.:63(4):738–749

Wulf, G., Shea, C. & Lewthwaite, R. (2010b) Motor skill learning and performance: a review of influential factors. Med. Educ. 2010: 44: 75–84

Yao, W., Fishman, M.G. & Wang, Y.T. (1994) Motor skill acquisition and retention as a function of average feedback, summary feedback, and performance variability. J. Mot. Behav. 26, 273–82

Young, D. E., Schmidt, R. A., & Lee, T.D. (2001) Skill learning: Augmented feedback In W. Karwowski (Ed.) International encyclopedia of ergonomics and human factors (pp. 558–561), London: Taylor and Francis

8

NEUROSCIENTIFIC ASPECTS OF IMPLICIT MOTOR LEARNING IN SPORT

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Motor learning has been defined as 'a set of [internal] processes associated with practice or experience leading to relatively permanent changes in the capability for responding' (Schmidt, 1988: 346). When the motor task is sufficiently complex that it requires the coordination of multiple degrees of freedom, as in the skills required for proficient performance in most sports activities, the learner tends to take a proactive role in aspects of the learning process that can be consciously monitored or controlled. At the heart of this chapter is the role of verbal-analytical processes in motor control and learning, taking as a primary distinction the contrast between processing of explicit, declarative or implicit, procedural knowledge during motor performance (e.g., Anderson, 1983; Anderson & Lebiere, 1998; Schneider & Shiffrin, 1977). We will first describe the nature of the knowledge that is involved in verbal-analytical processes and explore how accretion, storage and use of the knowledge are mediated by working memory. We will discuss a range of studies that provide insight into cortical aspects of working memory processes during learning and performance and we will introduce an overview of implicit motor learning, which has been developed as an approach to suppress verbal-analytical involvement during motor performance by controlling working memory input during learning. We will present neurophysiological evidence suggesting that implicit motor learning promotes neural efficiency by suppressing verbal-analytical involvement in motor performance and will try to show how this relates to individual differences in the propensity for conscious motor processing (reinvestment). Finally, we will briefly discuss studies that provide insight to neurophysiological aspects of implicit motor learning in rehabilitation, before trying to summarize the current state of our understanding of neuroscientific aspects of implicit motor learning in sport.

Two fundamental types of knowledge

Declarative knowledge refers to verbalizable rules, techniques or methods that are applied by verbal-analytical processes in an effort to advance learning and to achieve optimal