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Effects of bandwidth feedback on the automatization of an arm movement sequence

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ABSTRACT

We examined the effects of a bandwidth feedback manipulation on motor learning. Effects on movement accuracy, as well as on movement consistency, have been addressed in earlier studies. We have additionally investigated the effects on motor automatization. Because providing error feedback is believed to induce attentional control processes, we suppose that a bandwidth method should facilitate motor automatization. Participants ($N = 48$) were assigned to four groups: one control group and three intervention groups. Participants of the intervention groups practiced an arm movement sequence with 760 trials. The *BW0-Group* practiced with 100% frequency of feedback. For the *BW10-Group*, feedback was provided when the errors were larger than 10°. The *YokedBW10-Group* participants were matched to the feedback schedule of research twins from the *BW10-Group*. All groups performed pre-tests and retention tests with a secondary task paradigm to test for automaticity. The *BW10-Group* indicated a higher degree of automatization compared with the *BW0-Group*, which did not exhibit a change in automaticity. The comparison of the *YokedBW10-Group*, which also exhibited automatization, and the *BW10-Group* leads to the proposal that reduction of quantitative feedback frequency and additional positive feedback are responsible for the bandwidth effect. Differences in movement accuracy and consistency were not evident.

1. Introduction

Feedback is a powerful tool to support motor learning. In general, experiments have shown that improvements in performance were rapid in the presence of feedback (e.g., Newell, 1974), but extensive research has shown that augmented feedback that is presented too often can create a dependency on feedback and restrict long-term memory formation of a motor skill. At a minimum, this seems to be the case for settings involving program learning and higher amounts of practice (Marschall, Bund, & Wiemeyer, 2007). The guidance hypothesis (Salmoni, Schmidt, & Walter, 1984) suggests that two opposing processes are associated with the role of feedback in motor learning. During practice, feedback has a beneficial effect. It guides the learner toward the goal movement by providing information for error correction, but feedback also has a detrimental effect, as it urges the subject to continue to use its guiding properties to maintain performance. Consequently, the learner becomes dependent on it. According to the guidance view, this dependence may involve at least two distinct processes. First, when feedback is always available during practice, it becomes part of the task such that performance suffers

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when it is withdrawn in a retention test. In addition, feedback dependency might constrain the development of error-detection mechanisms. When error information is given externally (augmented feedback), the subject may be less likely to process the inherent response-produced feedback associated with movement production, and the performance will break down if the external feedback is withdrawn (Salmoni et al., 1984). The guidance hypothesis has been tested in several ways: changing the relative frequency of feedback (e.g., Winstein & Schmidt, 1990), delaying feedback (e.g., Liu & Wrisberg, 1997), and providing summary (e.g., Sidaway, Moore, & Schoenfelder-Zohdi, 1991) or bandwidth feedback (e.g., Sherwood, 1988). The guidance hypothesis does not refer to motor automatization as an important aspect of learning. While there is a large amount of data on how feedback influences performance (accuracy and consistency), the influence of feedback manipulations on motor automatization is mostly unknown. The majority of motor skills is presumably controlled with a high degree of automaticity as expertise increases (Fitts & Posner, 1967). In contrast, novices often involve a high amount of attentional resources to control their movement. In this context, attention can be characterized as a limited resource for information processing (Posner & Boies, 1971), such as working memory (Baddeley & Hitch, 1994) that might be involved in the recall and preservation of movement-related representations. According to Baddeley and Hitch (1974), working memory can be described as a system for the storage and conscious processing of information (see also Baddeley & Hitch, 1994). It is divided into a supervisory subunit (central executive) that controls the flow of information and storage-like subunits for visual–spatial (visual–spatial sketchpad) and verbal (phonological loop) content. The episodic buffer was added later and is dedicated to link content from different domains with a specific temporal structure (Baddeley, 2002). Movement-related representations in early stages of learning might be verbalizable movement rules (Maxwell, Masters, Kerr, & Weedon, 2001) that can be activated from long-term memory into the phonological loop or spatially coded sequences (Hikosaka et al., 1999) that can be activated from long-term memory into the visual–spatial sketchpad. Motor control can be described as attention-dependent in this case. During these early stages of motor learning, secondary tasks that also rely on the components of working memory will interfere with motor control processes due to the limited nature of the working memory resources. During extensive practice, the control shifts from a prevailing attentional control to a more automatic and working memory-independent control (Fitts & Posner, 1967), which goes hand in hand with shifts of neuronal activity during motor control (Doyon et al., 2009; Lohse, Wadden, Boyd, & Hodges, 2014). The availability of more free attentional resources over the course of practice is caused by a process that is often called *automatization* (Adams, 1971; Chein & Schneider, 2012; Fitts & Posner, 1967; Gentile, 1972; Keele, Ivry, Mayr, Hazeltine, & Heuer 2003; Logan, 1988; Shiffrin & Schneider, 1977). In conclusion, automatization is an important aspect of motor learning.

Error experiences during practice seem to be of special significance with regard to the level of automaticity that results from practice. Within the context of the errorless learning approach, Maxwell et al. (2001) propose that error experiences during practice primarily induce explicit, and thus attentional, control processes with the aim of movement corrections. Motor learning situations with frequent error experiences generate declarative knowledge as a consequence of testing strategies for error reduction (hypothesis testing). These processes rely on working memory resources (Baddeley, 2002; Baddeley & Hitch, 1974; Baddeley & Hitch, 1994). If there are fewer or no error experiences during practice, there will be a reduced explicit correction requirement and therefore a reduced involvement of attentional control processes.

Errorless motor learners have been found to be less dependent on attentional control processes as they are capable of concurrent performance of a cognitively demanding secondary task without disruption of their motor performance (e.g., Chauvel, Maquestiaux, Ruthruff, Didierjean, & Hartley, 2013; Masters & Maxwell, 2004; Masters, Poolton, & Maxwell, 2008; Maxwell et al., 2001; Poolton & Masters, 2005). Only a few studies have integrated delayed retention tests (Abdoli, Farsi, & Barani, 2012; Capio, Poolton, Sit, Eguia, & Masters, 2013; Capio, Poolton, Sit, Holmstrom, & Masters, 2013).

If movement outcome errors that are induced by relatively difficult learning environments clearly inform the learner regarding the movement deficits and initiate movement corrections, these suggestions could also be relevant for augmented feedback procedures. A higher augmented feedback frequency is presumably accompanied by a higher error signal frequency and is therefore likely to induce attentional control processes. On the other hand, an augmented feedback with lower rates of error signals could be beneficial for automatization processes.

A particular feedback manipulation that does not necessarily eliminate information content but reduces the frequency of error indications is the so-called *bandwidth feedback*. During a bandwidth feedback manipulation, augmented feedback is only presented if performance is beyond a predefined range of tolerance (Goodwin & Meeuwsen, 1995; Marschall et al., 2007; Wulf & Shea, 2004).

As a function of the range of tolerance, different frequencies of augmented feedback apply. This is only an ostensible feedback frequency reduction because the absence of feedback implies that the performance was within a certain target range (e.g., Lee & Carnahan, 1990; Sherwood, 1988). On the one hand, bandwidth feedback provides qualitative positive feedback when performance is within a certain range. On the other hand, quantitative error feedback is provided when performance is outside the specified bandwidth (Wulf & Shea, 2004).

Marschall et al. (2007) suggest that bandwidth feedback may be of particular advantage for learning because it integrates positive and eliminates negative guidance effects. Depending on the chosen bandwidth, missing augmented feedback acts as reinforcement, and given augmented feedback leads to the desired movement.

Studies on feedback valence show that feedback with positive valance compared with negative valence is more beneficial for learning (Bischoff-Grethe, Hazeltine, Bergren, Ivry, & Grafton, 2009; Lewthwaite & Wulf, 2010; Wulf, Chiviacowsky, & Lewthwaite, 2010; Wächter, Lungu, Liu, Willingham, & Ashe, 2009) and has been shown to influence neuronal activation patterns in feedback processing (Bischoff-Grethe et al., 2009; Seidler, Kwak, Fling, & Bernard, 2013; Wächter et al., 2009)