Using salient information for motor performance and learning

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Peter Leinen

Abstract

Human motor behavior includes a very wide range of movements such as grasping a cup to drink your coffee, playing a musical instrument such as the piano, or sports skills such as throwing a ball. Some of these skills are performed with one hand (unimanually) others simultaneously with both hands (bimanually). However, all of these skills have to be learned. In the domain of motor control and learning it is well documented that feedback is one potential learning variable that supports the learning process. Recent research has indicated that one important factor refers to the salient feedback information that a performer uses to increase motor performance and learning. Salient feedback information in this context not only supports the detection and correction of errors. It also forces the performer to achieve a stable performance pattern and improves the development of an efficient movement representation. This research involved three experiments which focused on the following issues: (1) determining the impact of availability and accessibility of salient feedback for the development of a movement sequence representation, (2) finding out at which hemisphere the movement sequence representation is represented, and (3) establishing the impact of salient feedback information during a life-span in a bimanual coordination task. The results indicate that performers have developed an efficient movement sequence representation depending on the available salient feedback information (Experiment 1) and that this information is represented in a specific hemisphere in our central nervous system (Experiment 2). Salient information also supports the performance of a multifrequency bimanual coordination task after 10 minutes of practice. However the performance changes in the course of a life-span (Experiment 3).

Zusammenfassung

Das menschliche Verhalten beinhaltet eine Vielzahl von Alltagsbewegungen, wie das Greifen einer Tasse, Bewegungen im musischen Bereich wie das Klavierspielen oder auch sportliche Bewegungen wie das Werfen eines Balles. Einige dieser Bewegungen werden mit einer Hand ausgeführt (unimanuell) andere gleichzeitig mit beiden Händen (bimanuell). Gemein allen diesen Bewegungen ist das sie erlernt werden müssen. In der Literatur ist gut dokumentiert, dass Feedback eine Lernvariable ist, welche die Lernprozesse unterstützen kann. Aktuelle Forschungsergebnisse zeigen, dass eine wichtige Komponente in der Salienz von Feedbackinformationen besteht. Dies bedeutet welche Informationen werden aus der Vielzahl von Informationen die dem Lernenden zu Verfügung stehen herausgehoben und somit dem Lerner leichter zugänglich gemacht damit dieser eine effiziente Bewegungsrepräsentation für die motorische Ausführung etablieren kann. In drei Experimenten wurde den Fragen nachgegangen (1) ob in Abhängigkeit der Verfügbarkeit und Zugänglichkeit von Feedback eine Bewegungsrepräsentation etabliert werden kann, (2) wo die Informationen über die Bewegungsrepräsentation in unserem Zentralnervensystem abgespeichert werden und (3) ob saliente Informationen die motorische Ausführungsleistung über die Lebenspanne bei einer bimanuellen Koordinationsaufgabe unterschiedlich beeinflussen. Die Ergebnisse zeigen, dass in Abhängigkeit der Salienz von Feedbackinformationen Lerner eine effiziente Bewegungsrepräsentation basierend auf visuell-räumlichen oder motorischen Informationen entwickeln (Experiment 1) und diese Informationen hemisphärenspezifisch in unserem Zentralnervensystem abgespeichert werden (Experiment 2). Saliente Informationen ermöglichen es den Lernern zudem, bimanuelle multifrequenzielle motorische Aufgaben bereits nach weniger als 10 Minuten Übung auszuführen. Die Leistung ist aber über die Lebensspanne graduell unterschiedlich (Experiment 3).

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1 Introduction

To establish learning processes and increases in performance all kinds of systems take advantage of various feedback mechanisms. The complexity of feedback mechanisms ranges from a simple heater-thermostat unit in a room which is using the thermostat as an information feedback channel to high-end technical systems like autonomous cars, which incorparate a plurality of different sensors to process internal and external feedback in order to ensure a safe and successful arrival at the right destination. One of the most complex systems, however, is the human motor system and it remains far from being perfectly understood. The human motor system controls our daily actions, can rapidly learn new skills and always seeks to optimize its performance. In order to do so, the human motor system uses several different information channels to obtain the necessary feedback information in order to reach its goals and improve its performance.

Adams (1971) proposed that motor learning processes are shaped and improved through the refinement of perceptional-motor feedback loops. A motor task like grasping a glass, for example, is a process in our motor system that provides perceptional feedback information to reduce errors in the repetitions of the task. A mix of feedback information is involved in this task. Visual-perceptional information provides the motor system with basic information about the target itself and the system's spatial relation to the target. But further supporting feedback information is proceeded in this task, e.g. haptic information to control the strength of the grasp or proprioceptic information to estimate the right force to lift the glass.

According to Adams (1971), feedback provides information helping to solve the motor problem by guiding the movement to the target on successive trials. He suggested that feedback does not directly produce learning, but, it creates the appropriate situation (i.e., being on target) so that the actual learning mechanisms can operate (i.e., the movement's feedback producing an increment in “strength” for the perceptual trace). This source of information is thought to serve as a basis for error detection and correction on subsequent trials and thus can be used to achieve more effective performance as practice continues.

According to the literature on motor learning, one of the most important variables in the learning of motor skills is the information provided by extrinsic feedback regarding the progress and outcome of performing movements. This visual-perceptual information can be presented through concurrent and terminal feedback (Adams, 1971; Bilodeau & Bilodeau, 1958). A lot of research has been done on the topic of visual-perceptual feedback and provided evidence that there are all kind of parameters that influence our motor system in the way it deals with visual-perceptual feedback information. More than a century ago Woodworth (1899) already described the influence of the visual-perceptual feedback on the control modes subjects choose for their motor action. His subjects were given the task to draw a line on a piece of paper in a back-and-forth movement. The execution speed was controlled by a metronome and was gradually increased. In one condition, his subjects kept their eyes open during the execution and in the second condition subjects had to close their eyes. The results showed the accuracy advantage of the open-eyes group in the trials with a lower velocity versus the closed-eyes group. This advantage in accuracy steadily shrank with the increase of movement velocity. Woodworth deducted from these results that the movements of both groups were initialized as pre-programmed movements, but the eyes-open-group was able to use their visual-perceptual information (or what he called *current control*) during the execution to reduce their movement errors, at least as long the movement velocity still gave them the opportunity to use the feedback in their action. This so called *critical velocity* describes the time mark in the duration of an action at which visual-perceptual feedback can be included in the motor control process and be used for error correction. This critical time was estimated by Woodworth to be around 200ms. This has largely been confirmed by later researches (e.g. Keele & Possner, 1968). These early findings lead to the conclusion that visual-perceptual feedback always depends on the context of its action. In this case, the value of the feedback information changes in contrast to the duration of the original action.

In research on motor learning and performance there has always been a great effort to present feedback information most accurately in order to provide optimal support for learning and performance. As mentioned before, which still today has high relevance for the understanding of the mechanisms behind processing feedback information is the closed-loop theory of motor learning by Adams (1971). The basic idea of this theory is that the learners develop a perceptual trace based on the various types of feedback information generated through their action. This perceptual trace is used for an ongoing comparison versus a stored set of sensory consequences to reduce errors in future performances. The model is based on an engineering analogy, also known as negative feedback loop, and is consistent with previous findings on the role of feedback in learning and performance (e.g., Adams, 1968; Bilodeau, 1966).

To better support this negative feedback loop, feedback information can be modified and optimized. This optimized feedback information can also be described as salient information. In general, salient information is characterized by pieces of multimodal perceptual information, which before, during or after a movement is more readily accessible to the learner, to improve motor performance and motor learning. Salient perceptual information facilitates pattern detection and improves error detection and correction processes to increase stable performance through practice (see Shea et al., 2016).

Salient feedback information is a way to optimize this negative feedback loop by providing modified information, making it easier and more efficient for the motor system to detect and minimize errors. In other words, developing more salient feedback information is like switching from a roadmap to a navigation system to find a certain street in an unknown city. A map in combination with the knowledge of your current location provides all the necessary information to find a final destination and enables the user to look at the map at anytime to correct his direction. But the map does not present the most needed piece of information. All information required to reach a destination is embedded in the sum of all the information this map can provide to the viewer. And the viewer has to make an effort to extract the specific feedback information needed at this point. In contrast, most mobile navigation systems provide the user with a reduced amount of information based on their current location. Some devices even display new information only before a direction change. The navigation system displays salient feedback information which is reduced to a set of core facts and pre-processed for better flawless integration into our primary feedback loop, so that the user can navigate the vehicle to the final destination.

In the experiments conducted in the framework to this thesis the type of salient information is also a visual information aiming to support a person in optimizing their negative feedback loops. The visual salient information here is represented in two different modes in which a computer cursor is controlled by one or two arm-levers.

In experiment 1 and experiment 2 the presented salient feedback information supports the performer in learning a unimanual movement sequence. In some of the conditions of these two experiments the performers can see the cursor and a representation of the target movement sequence and are provided with a visual online feedback of the spatial and temporal differences of their concurrent movement production. Afterwards, in all conditions the performers are given a KR (knowledge of result) feedback. The produced movement sequence is displayed as a graphical overlay on the representation of the target movement sequence. This also provides the performers a simplified visual comparison of the produced movement sequence and the differences in spatial and temporal dimensions.

In experiment 3, the task and the characteristics of the salient feedback information are altered. The task switches from a unimanual task to a bimanual task. The salient feedback information addresses the bimanual coordination problem of the task. To support the performer, the salient feedback information of both limbs is compressed into one displayed cursor. Reducing the amount of visual information in this salient feedback information makes it easier to integrate it into a negative feedback loop.

2 Theoretical background

With this context dependency of visual-perceptual feedback in mind, this thesis and its experiments offer further perspectives on how salient information in the form of visual-perspective feedback influence the way we learn and perform different motor tasks.

The way movement sequences are represented and processed in our brain is an important research topic in the field of motor control and learning. It started with the work of Lashley (1951) and the topic is still very visible in recent research groups (Bapi, Miyapuram, Graydon, & Doya, 2006; Hikosaka, Nakamura, Sakai, & Nakahara, 2002; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Kirsch & Kunde, 2012; Korman, Raz, Flash, & Karnim, 2003; Nakahara, Doya, & Hikosaka, 2001; Shea & Kovacs, 2013; Shea & Wright, 2012; Tanaka &Watanabe, 2014). A main conclusion of these research groups is that there seems to be some evidence that independent codes or representations during the acquisition of a movement sequence are developed and the availability of several pieces of information, like salient information, assist the learning process (Keele et al., 2003). In addition, most of these theoretical frameworks describe a change in the representation during the acquisition phase (Bapi et al., 2006; Dirnberger & Novak-Knollmueller, 2013).

A consistent theoretical framework is the parallel neural-network model of Hikosaka et al. (1999). It is based on behavioral and neuronal imaging data (Bapi, Doya, & Harner, 2000; Hikosaka et al., 1999, 2002). Hikosaka et al. (1999) describe the development of two parallel representations during the acquisition of a movement sequence. One neural stream is a fast developing representation based on a visual-spatial coordinate system (e.g., spatial locations of the end effector and/or sequential target positions, effector-independent) and the second one, is a contemporaneous but slower developing representation which bases on a motor coordinate system (e.g., sequence of activation patterns of the agonist/antagonist muscles and/or achieved joint angles, effector-dependent). According to this framework, the reaction of the parallel neural-network model to further practice is an alternating shift of reliance from the fast developing visual-spatial coordinate system to the slower developing motor coordinate system (Hikosaka et al., 1999; Bapi et al., 2000).

Besides practice, it seems there are additional parameters which have an impact on the more efficient coordinate system for sequence production. Moreover, the complexity (for example the amount of reversals and/or the duration) of the movement sequence and the availability of concurrent visual feedback seem to influence the preference toward the dominating coordinate system in the sequence production (Panzer, Krueger, Muehlbauer, Kovacs, & Shea, 2009; Shea et al., 2011). The results of Kovacs, Boyle, Gruetzmacher, and Shea (2010) provide a more detailed example. They showed that the availability of concurrent visual feedback and the possibility of online control in a movement sequence resulted in a stronger preference for the visual-spatial coordinate system. In contrast, if concurrent visual feedback was prevented, the participants showed a better performance in the motor transfer test, which implies a preference for the motor coordinate system.

Based on the results, our follow-up question is to know whether it is possible to switch coding schemes (motor and visual-spatial) and control modes (online and pre-planed control) after the acquisition depending on the type of salient information which is presented.

In accordance to the theoretical framework of Hikosaka et. al. (1999) it should be possible to access both coordinate systems regardless of the performers' learning stage or their actual status. Depending on the available salient information, subjects use the most successful code for sequence production irrespective of the stage of practice (see also Clegg, DiGirolamo, & Keele, 1998; Kovacs, Han, & Shea, 2009).

Furthermore this is a relevant question with regard to the perspective of control modes. According to Glover (2004) and the older works of Woodworth (1899), our motor control system is able to alternate between pre-planned control and online control, but it naturally chooses the more efficient control mode depending on the context of the task (e. g. the availability of feedback and the kind of task). Based on these assumptions of Glover's (2004) planning-control model, the leading question in this first experiment helps to further understand how flexible the subjects are in their choice of control modes and to what extent subjects are able to switch the executed control mode through a change in the availability of salient information at a certain point after the task acquisition.

The outcome of the first experiment leads us to a shift from the starting question of *how* movement-related information is influenced by manipulating the supporting salient information to the follow-up question of *where* this movement-related information is stored and proceeded after the acquisition with the support of salient information.

To obtain answers to this question we combined for the first time the idea of the intermanual-transfer-test paradigm with a recognition test based on the visual-half-field (VHF) paradigm. There already have been experiments which combined the idea of intermanual-transfer-test and the visual-half-field paradigm, but in a different application and for other purposes. Ellenbuerger et al. (2012) and Schmitz et al. (2013) have conducted experiments, where visual information about a sequence was presented in different VHF during sequence acquisition in order to investigate the encoding of a sequence representation in the two hemispheres. They used the visual-half-field paradigm to project information directly on a specific hemisphere. This was done during acquisition and without physical exercise. Based on this thesis the visual information Ellenbuerger et al. (2012) and Schmitz et al. (2013) used in their experiments can be classified as salient information. In the first experiment of this dissertation the focus was on the time required to recognize the stimulus in a visual-half-field shortly after the physical acquisition of a movement sequence.

The basic assumption of the visual-half-field paradigm is based on inter-hemispheric transmission and the physiological structures of the crossed visual pathways. Visual stimuli presented selectively to either the left visual field (LVF) or the right visual field (RVF) are initially projected directly to the contralateral hemisphere (Bourne, 2006). The latency a subject needs to respond to a stimulus presented in either of the VHFs reveals details about the hemispheric origin of the information processing. If the response time of a stimulus presented in the RVF is lower compared to the response time of the same stimulus presented in the LVF, this means the origin of the response production is based on the left brain hemisphere. The higher response time that comes with a LVF presentation must be traced back to the detour the stimulus information takes from the right brain hemisphere over the corpus callosum to the left brain hemisphere, which is the main proceeding brain hemisphere for this information and resulting response production (Hardyck, Tzeng, & Wang, 1977; Kinsbourne, 1970; Poffenberger, 1912; Berlucchi, Aglioti, & Tassinari, 1994 for a review).

A further advantage and additional feature of the VHF-paradigm are in contrast to the intermanual-transfer-test, as it reduces possible lateralization effects caused through the handedness of the learner. This can be ascribed to the fact, that motor information is only recognized after acquisition by a response through a bimanually keypress and not physically reproduced with unilateral limb movement.

In the last step of these experiments we extended the use of salient information by modifying the task. At first we used salient information in different presentation modes as support in the acquisition of a unimanual task. In the last experiment we used salient information as concurrent feedback to support the execution of a continuous 1:2 bimanual coordination task. The task itself asks the subject to make a continuous extension-flexion movement with both of their limbs. This had to be done in a manner so that one limb had to move twice as fast as the other limb. These limb movements result in a continuous change between the symmetrical and the non-symmetrical mode of coordination while performing the task (Swinnen, Dounskaia, Walter, & Serrien, 1997). Because of this dynamical change task was hard to learn. But with visual online support of salient information, the subjects were able to produce an effective performance of this task after a few minutes of practice. The salient information provided in this task was an online Lissajous feedback. Lissajous display presents the integrated movement of the two limbs as a cursor in one plane, where the movement of the right limb, for example, moves the cursor to the right (extension) and left (flexion), while the movement of the left limb moves the cursor up (extension) and down (flexion) on the display. This compressing of the movement information of both limbs results in optimized perceptual information and reduced attentional demands for the learner (see Shea et. al., 2015 for review).

In addition to this, the driving idea in this last experiment was to trace the development of the bimanual skill acquired with the support of salient information over a subject’s life span. As shown in motor development research children and older adults have a stronger tendency for mirror movements in bimanual coordination tasks than young adults (e.g., Addamo, Farrow, Bradshaw, & Georgiou-Karistianis, 2011; Cattaert, Semjen, & Summers, 1999; Cohen, Taft, Mahadeviah, & Birch, 1967; Conolly & Stratton, 1968; Walter & Swinnen, 1990b; Wolff, Gunnoe, & Cohen, 1983). Throughout life this tendency decreases in children, but increase again in older adults. There is some evidence that both changes are connected to transformations of the corpus callosum. For children the tendency decreases with the time of the completion of the myelination of the corpus callosum (e.g., Chicoine, Proteau, & Lassonde, 2000; Serrien, Sovijärvi-Spapé, & Rana, 2014; Yakovlev & Lecours, 1967). For older adults the reappearance of these mirror movement tendencies co-occurs with age-related degenerative processes of the callosal structures, i.e., the demyelination of the callosal fibers (e.g., Pfefferbaum et al., 2000; Salat et al., 2005).

3 Overview

The main contents of this thesis are three experiments presented in published journal articles which highlight the role of salient information in motor performance and learning.

In experiment 1 (“*The impact of concurrent visual feedback on coding of on-line and pre-planned movement sequences*”) the main purpose of the experiment was to determine if the availability of salient information during an acquisition influences the preference of our motor control system for one of the two parallel coordinate systems (visual–spatial, motor). Another research question was as to how flexible the motor control system is, if the availability of the salient information suddenly changes.

The task was to reproduce a 2000ms spatial-temporal pattern of a sequence of elbow flexions and extensions. Subjects were randomly assigned to one of the two conditions, online (OL) or pre-planned (PP). In the OL condition the criterion waveform and the cursor were provided during movement production while this information was withheld during movement production for the PP condition. The task was embedded in an inter-manual transfer design. After the retention test an additional subdivision was introduced. One half of the subjects stayed in their condition (PP->PP or OL->OL) and the other half switched the condition for the transfer tests (PP->OL or OL->PP). The mirror effector transfer test required the same pattern of muscle activation and limb joint angles as required during acquisition. The non-mirror transfer test required movements to the same visual-spatial locations as experienced during acquisition.

Experiment 2 (“*Hemispheric asymmetries of a motor memory in a recognition test after learning a movement sequence*”) answers the question on where, i. e. on which brain hemisphere, the more efficient coordinate system for sequence production is represented. This experiment is divided in two sub-experiments. In sub-experiment 1, dominant right-handers were randomly divided into one of two acquisition groups: a left-hand starter and a right-hand starter group. After an acquisition phase, reaction time (RT) was measured in a recognition test by providing the acquired sequential pattern in the left or right visual half-field for 150 ms. The recognition test was embedded in a visual-half-field design. In a retention test and two transfer tests the dominant coordinate system for sequence production was evaluated. In sub-experiment 2 dominant left-handers and dominant right-handers had to acquire the sequence with their dominant limb.

Finally, in the third experiment ("*Life span changes: Performing a continuous 1:2 bimanual coordination task*") the perspective changes from a unimanual to a bimanual task. The research interest was to find out how a person's age influences the execution of the newly acquired bimanual skill, which was acquired with the support of salient information feedback.

Children, young adults, and older adults were instructed to perform a continuous 1:2 bimanual coordination task by performing flexion-extension wrist movements over 30s where symmetrical and non-symmetrical coordination patterns alternate throughout the trial. The vision of the wrists was obstructed and salient information in form of Lissajous-feedback was provided online. All age groups had to perform 10 trials under three different load conditions (0 kg, .5 kg, 1.0 kg: order counterbalanced). The load was manipulated in order to determine if heavier load increases the likelihood of mirror movements.

3.1 Overview about the conducted experiments

Experiment 1

Authors: Leinen, P., Shea, C. H. & Panzer, S.

Title: "The impact of concurrent visual feedback on coding of on-line and pre-planned movement sequences"

Contribution of Peter Leinen: planning; organization; data acquisition; data analysis; authoring of the manuscript

Status: published in Acta Psychologica, 2015

Experiment 2

Authors: Leinen, P., Panzer, S. & Shea, C. H.

Title: "Hemispheric asymmetries of a motor memory in a recognition test after learning a movement sequence"

Contribution of Peter Leinen: planning; organization; hardware development (eye tracker); data acquisition; data analysis; authoring of the manuscript

Status: published in Acta Psychologica, 2016

Experiment 3

Authors: Leinen, P., Vieluf, S., Kennedy, D., Aschersleben, G., Shea, C. H. & Panzer, S.

Title: "Life span changes: Performing a continuous 1:2 bimanual coordination task"

Contribution of Peter Leinen: planning; organization; data acquisition; data analysis; authoring of the manuscript

Status: published in Human Movement Science, 2016

3.2 Overview about further publications

Authors: Leinen, P. & Panzer, S.

Title: “Entwicklung eines trainerfreundlichen Messplatzes in einer Schwimmhalle mit Open Source Tools.”

Contribution of Peter Leinen: planning; organization; hardware development; authoring of the manuscript

Status: published in DVS Sportinformatik - Abstract- und des Proceeding-Band, 2016

Authors: Vieluf, S., Massing, M., Blandin, Y., Leinen, P. & Panzer, S.

Title: “The role of eye movements in motor sequence learning”

Contribution of Peter Leinen: planning; data analysis; authoring of the manuscript

Status: published in Human Movement Science, 2015

Authors: Malangré, A., Leinen, P. & Blischke, K,

Title: “Sleep-related offline learning in a complex arm movement sequence.”

Contribution of Peter Leinen: planning; organization; data analysis

Status: published in Journal of Human Kinetics, 2014

3.3 Overview about conference talks with review of the submitted abstract

Authors: Leinen, P. & Panzer, S.

Title: “Entwicklung eines trainerfreundlichen Messplatzes in einer Schwimmhalle mit Open Source Tools ”

Contribution of Peter Leinen: Presenter

Conference: DVS Conference “Sportinformatik”, 2016

Authors: Leinen, P. & Panzer, S.

Title: “Pointing movements and visual illusion: van Donkelaar (1999) revisited.”

Contribution of Peter Leinen: Presenter

Conference: NASPSPA Conference, 2016

Authors: Leinen, P., Panzer, S. & Shea, C.H.

Title: “Does ischemia influence effector transfer?”

Contribution of Peter Leinen: Presenter

Conference: NASPSPA Conference, 2015

Authors: Panzer, S., Leinen, P. & Shea, C.H.

Title: “Is the motor coordinate system lateralized in the left hemisphere?”

Contribution of Peter Leinen: in cooperation with Stefan Panzer

Conference: NASPSPA Conference, 2014

Authors: Panzer, S. & Leinen, P.

Title: “Lateralisierte Wissensrepräsentation von Sportgeräten.”

Contribution of Peter Leinen: Presenter

Conference: DVS Conference “Motorik”, 2013

4 Experiment 1 - The impact of concurrent visual feedback on coding of on-line and pre-planned movement sequences

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5 Experiment 2 - Hemispheric asymmetries of a motor memory in a recognition test after learning a movement sequence

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6 Experiment 3 - Life span changes: Performing a continuous 1:2 bimanual coordination task

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7 General discussion and outlook

This dissertation contributes to a better understanding of the human motor control system. According to Rosenbaum (2009) the subject of motor control can be structured into four core problems:

- the degrees of freedom problem
- the sequencing and timing problem
- the perceptual-motor integration problem
- the learning problem

The experiments in this thesis specifically address the latter two: how are perception and motor control combined? How are perceptual-motor skills acquired? The results of these experiments can be summed up into five main findings.

First, providing visual salient feedback information during the acquisition of a movement sequence is crucial for this kind of representation. If a visual salient feedback is concurrently provided, it stimulates a visual-spatial representation. But, if visual salient feedback is withheld, the acquired sequence tends to take a form of a motor coordinate representation (experiment 1).

Second, if the subjects develop a preference for a more efficient movement representation one day after the acquisition, this does not mean the motor system cannot fall back on the alternate representation. If the extrinsic salient feedback condition suddenly changes by covering salient feedback, the motor system adapts to the new condition and is able to access a motor coded representation (experiment 1).

Third, if the motor coordinate representation is the dominant representation for a task, its information is mainly localized on the left brain hemisphere (experiment 3).

Fourth, salient information can be used to reduce the amount of attention consuming processes in a difficult 1:2 bimanual coordination task. By using the concept of a Lissajous template the visual feedback information of two hands can be compressed in a single cursor. This relieves attentional processes during an online controlled execution and simplifies bimanual coordination.

Fifth, this support through preprocessed and reduced salient feedback information by using a Lissajous template works on all three age groups in this experiment (children, young adults and older adults). However, performance differs between these groups. Performance over age groups can be described as an inverted-U-function. Middle-aged young adults out-perform both of the other groups.

In the follow-up section it will be discussed in more detail how this finding have a share in the above mentioned two core problems of motor control.

7.1 The learning problem

What Rosenbaum (2009) named the fourth core problem is the question of how motor skills are acquired. The first two experiments described in this thesis deal with the influence of salient information on learning processes, or, to be more specific, learning a movement sequence of a spatial-temporal movement sequence. The first result (see above) shows how the learning process is deeply codetermined by the extrinsic feedback modalities the learner is equipped with during acquisition. This is not a new finding. The influence of extrinsic visual information on our performance has been an active research field since Woodworth (1899). As argued in experiment 1 and already in previous research by Kovacs, Boyle, Gruetzmacher and Shea (2010), the learner operates in a pre-planned control-mode if salient information is withheld during execution in the acquisition phase. If information is given the learner operates in an online controlled mode. These control modes based on Glover's (2004) concept are related to Rosenbaum's (2009) concept, which propose that motor learning uses forward and inverse models to improve during the acquisition of a skill. Furthermore, supporting a motor task during acquisition also influences what the learner believes is the more efficient coding system (motor vs. visual-spatial) to rely on.

Based on the second main findings it can be assumed that the motor control system during a learning process does not only develop the most efficient representation of a motor sequence under the given conditions. Like Hikosaka et. al. (1999) already proposed in their model, the less efficient representation is developed as well. With changing conditions, like withdrawal of the salient information, the motor system can immediately fall back from the primary stream of visual-spatial coded information to the secondary stream of motor-coded information and keep up its performance as far as possible.

The third main finding of experiment 2 clarifies in the context of learning the localization of motor-coded information directly after an acquisition. The results from these two sub-experiments offered further evidence for an asymmetry of the human brain hemispheres. Independent of handedness motor coded information seem to be stored on the left brain hemisphere. This main finding supports the concept of brain hemisphere specialization (Liepmann, 1905; Kimura, 1977; Serrien and Sovijärvi-Spapé, 2015) and helps to get a deeper understanding of the neural level of motor learning.

Experiment 3 is not directly connected to a review of learning processes. There was no retention test after a certain time period and no control condition if the acquired bimanual coordination pattern outlasted a certain time period, which is a basic requirement for learning in general.

7.2 The perceptual-motor integration problem

The question of how motor learning is established is intertwined with the question of perception-motor integration. To improve motor learning processes a learner is dependent on some kind of feedback. It is the basic mechanism to detect errors and correct these on the fly or in further trials. As already mentioned in the introduction, visual feedback is one of the most powerful feedback channels of the human motor system and salient information is a way to make this visual feedback easier to process. But modulating feedback always has some kind of impact on the whole motor performance and learning process. Besides the already mentioned influence of the availability of salient feedback on our motor control-mode and the kind of representation knowledge, salient information can also accelerate the acquisition processes. What is listed as the fourth of the main findings of this dissertation describes how perceptual processing can be reduced in a 1:2 continuous bimanual coordination task, which results in a better integration into the motor control system.

This kind of multi-frequency ratio task, which consists of an alternating in-phase/anti-phase pattern is quiet a challenge for a novice performer (e.g., Byblow & Goodman, 1994; Sternad, Turvey, & Saltzman, 1999a, 1999b; Treffner & Turvey, 1993; Swinnen, Dounskaia, Walter, & Serrien, 1997). Without the presented salient information the performer would have to invest a lot of time to manage the task, but displaying salient information in form of Lissajous feedback and template, the performer can manage this task in about 5 min (Kovac, Buchanan & Shea, 2010). An explanation for the impressive support of this kind of salient information in this task is based on perceptual constraints. The performers have to split their attention on two effectors at the same time. Additionally, the effectors are in a continuous change between stable and less stable coordination patterns. This perceptional split and ongoing change in coordination patterns is hard to manage for the motor system (Shea, Buchanan & Kennedy, 2015). An online controlled task like in this experiment relies on a steady and fast feedback integration. By compressing the feedback into a single attention point perceptual feedback integration is facilitated and biomechanical constraints of the altering shift between stable and less stable coordination patterns can be overwhelmed (Shea, Buchanan & Kennedy, 2015). Furthermore, the fifth main finding suggests that this advantage (offered by a facilitated visual feedback integration) is available to performers regardless of their age. The findings of age-related differences are in accordance to other research which has demonstrated that children and older adults showed a strong tendency to produce mirror movements (e.g., Addamo et al., 2009; Wolff et al., 1983).

7.3 Outlook

Based on the main findings of this dissertation and the highlighted links between salient information and motor learning/performance, it becomes clear that salient information has a huge impact on the way our motor system processes information. These interactions should always be considered in future research in the field of motor learning and performance. A further approach resulting from the findings of experiment 1 and experiment 2 would be to ask if changing access to salient information during performance does not only change the coding mode of the acquired information and the control-mode during the task, but also influences which brain hemisphere is dominantly involved in the process. Furthermore, it will be interesting to find out if this hemisphere dominance also switches by changing the access to salient information. To answer this question it would be necessary to extend the domain of behavioral research to a neural brain imagery level, like monitoring electroencephalography (EEG) activity during the execution of a unimanual movement sequence. By comparing the motor cortex area activity of both brain hemispheres, it could be possible to detect a change in hemisphere dominance under different salient information conditions. The results of an experiment like this would probably be a further step to help integrate the findings of this dissertation and its underlying theoretical concepts into a neural structural correlate, which is widely discussed in the domain of brain hemisphere specialization (Haaland & Harrington, 1989; Harrington & Haaland, 1992; Kimura, 1977; Mutha, et al., 2012; Serrien, et. al., 2006 for overviews).

Another connection point of further research would be to close the experimental gap between the work of Ellenbuerger et. al. (2012) and experiment 2 in this dissertation. Ellenbuerger et. al. (2012) analyzed how presenting information in different visual-half-fields in a pure observational learning setting influences the performance in a physical execution transfer-test the next day. Their result showed an advantage for visual-spatial coded information, if the information was presented in the visual central field or right-half-field. Experiment 2 of this dissertation found evidence of a right-visual-field advantage for recognition motor-coded information after a physical acquisition. A question arising from these two experiments is to know whether presenting salient information in a benefited half-field during a physical acquisition would lead to an advantage in performance. To answer this question would require an experiment which ensures an exclusive presentation of the information in the specific half-field. This could be implemented by using a head-mounted-display or a virtual reality headset. Potential results of such an experiment would also be interesting from the perspective of applied science. The arrangement of information on head-up-displays, for example in cars, could be improved by considering these findings.

The last of the three experiments shows how it is possible to use manipulate salient information in order to achieve a huge performance gain in a very difficult bimanual coordination task. This idea of optimizing salient information in other complex coordination tasks deserves more attention, particularly in the field of applied science. Rehabilitation research, for example, could improve methods for relearning disrupted coordination patterns after a stroke. In sports or when learning musical instruments, it is often a hard challenge for the learner to adopt complex coordination patterns, like doing gymnastics or playing the guitar. With today’s possibilities, which range from smartphone applications to real time full body motion tracking, these challenges could be lowered (especially for novices) by additionally presenting compressed salient feedback information during the initial learning phase.

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Declaration of Authorship

I hereby certify that this dissertation has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

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