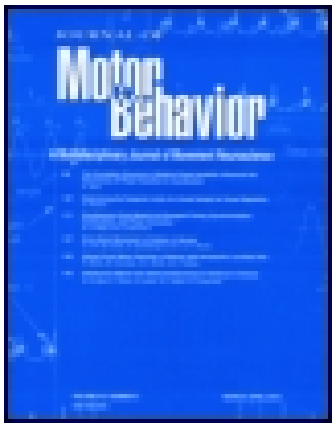
This article was downloaded by: [Universitaetsbibliothek Bielefeld]
On: 13 September 2014, At: 02:50
Publisher: Routledge
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Motor Behavior
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/vjmb20

The Functional Role of Cognitive Frameworks on Visuomotor Adaptation Performance

Heiko Lex[ab], Matthias Weigelt[c], Andreas Knoblauch[de] & Thomas Schack[abf]

[a] Neurocognition and Action - Research Group, Bielefeld University, Germany

[b] Cognitive Interaction Technology - Center of Excellence (CITEC), Bielefeld University, Germany

[c] Department of Sport and Health, University of Paderborn, Germany

[d] Honda Research Institute Europe, Offenbach, Germany

[e] Engineering Faculty, Albstadt-Sigmaringen University, Albstadt, Germany

[f] Research Institute for Cognition and Robotics (CoR-Lab), Bielefeld University, Germany

Published online: 10 Sep 2014.

To cite this article: Heiko Lex, Matthias Weigelt, Andreas Knoblauch & Thomas Schack (2014): The Functional Role of Cognitive Frameworks on Visuomotor Adaptation Performance, Journal of Motor Behavior

To link to this article: http://dx.doi.org/10.1080/00222895.2014.920290

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Journal of Motor Behavior, Vol. 46, No. 6, 2014
Copyright © Taylor & Francis Group, LLC

RESEARCH ARTICLE

The Functional Role of Cognitive Frameworks on Visuomotor Adaptation Performance

Heiko Lex[1,2], Matthias Weigelt[3], Andreas Knoblauch[4,5], Thomas Schack[1,2,6]

[1]Neurocognition and Action – Research Group, Bielefeld University, Germany. [2]Cognitive Interaction Technology – Center of Excellence (CITEC), Bielefeld University, Germany. [3]Department of Sport and Health, University of Paderborn, Germany. [4]Honda Research Institute Europe, Offenbach, Germany. [5]Engineering Faculty, Albstadt-Sigmaringen University, Albstadt, Germany. [6]Research Institute for Cognition and Robotics (CoR-Lab), Bielefeld University, Germany.

ABSTRACT. The authors investigated the effects of cognitive representations of movement directions on sensorimotor adaptation performance. Adaptation performance was measured via a pointing experiment in which participants were provided with visual feedback that was distorted along the midsagittal plane (i.e., left-right reversal). Performance was analyzed relative to participants' individual adaptation gains and 3 groups were subsequently defined (i.e., skilled, average, and poor adapters). The group separation was kept for the Cognitive Measurement of Represented Directions, which was used to analyze participants' cognitive representation of movement directions. The results showed that skilled adapters, in contrast to poor adapters, possess a global representation of movement directions aligned to the cardinal axes. The cognitive representation structure hence supports the sensorimotor adaptation performance.

Keywords: cognitive representation, motor learning, movement direction, sensorimotor adaptation

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

Sensorimotor adaptation can be characterized as a learning process, which is driven by the formation of new links between motor output and sensory feedback (Ferrel, Bard, & Fleury, 2001). The present scientific research on the cognitive principles responsible for sensorimotor adaptation focuses on the modification characteristics of an internal model as one kind of internal representation of environmental properties (Wolpert, Ghahramani, & Jordan, 1995). Modifications of an existing internal model toward visual disturbances can be stored in memory: something that, among other things, can be seen in a reduced error when adapting to a similar disturbance for the second time (Abeele & Bock, 2001). Previous research demonstrated that such a modified internal model persists over time and can be retained for more than a month (Bock, Schneider, & Bloomberg, 2001).

To overcome the initial performance disruption at the beginning of distorted trials, other processes than transformations of the internal model must be activated (Bock, 2005; Redding & Wallace, 1996). These processes can be described as a gradual adaptation to new environmental conditions as strategic control, which basically relies on cognitive representations (Mazzoni & Krakauer, 2006). Evidence for this assumption was previously provided by a study that investigated the adaptation performance of a deafferent patient (i.e., a patient with a neurological disorder blocking sensory feedback from the neck on downward). A further decrease in the adaptation performance was found when the patient was engaged in an additional cognitive task (e.g., counting task), compared to a healthy control group (Ingram, van Donkelaar, Cole, Vercher, Gauthier, & Miall, 2000). This finding provided evidence that cognitive processes are involved in sensorimotor adaptation, but it still remains unclear, however, which strategic cognitive processes are responsible for the sensorimotor adaptation performance.

Within the classical research paradigm of goal-directed pointing experiments, the cognitive representation of movement directions has previously been found as one functional indicator to measure sensorimotor adaptation performance (Lex, Weigelt, Knoblauch, & Schack, 2012). Lex et al. provided evidence for the existence and specifics of cognitive representations of movement directions, when the movement directions are presented in a proprioceptive-visual mode. According to their results, differences in sensorimotor adaptation behavior between different groups of participants are caused by different cognitive representations of movement directions (i.e., global and local representations). Global representations of movement directions are aligned to the cardinal axes in the sagittal and horizontal plane. In contrast, local representations of movement directions are aligned to neighboring movement directions (i.e., 30° apart from each other). Global cognitive representations of movement directions have been found to lead to a better adaptation performance in a task, in which visual feedback was distorted via a left-right reversal (i.e., a mirroring along the sagittal axis). The termini *global* and *local* are used herein with emphasis to the organization of corresponding movement directions.

Sensory motor adaptation performance has also been shown to be influenced by different sensory input modalities (e.g., visual, kinesthetic, proprioceptive feedback) in accordance with the adjusted distortion (van Beers, Wolpert, & Haggard, 2002). For example, in a sensorimotor adaptation toward a distortion of the visual feedback in terms of a sagittal displacement humans tend to rely more on proprioceptive movement feedback. However, during the adaptation toward a distortion in terms of a horizontal

Correspondence address: Heiko Lex, Bielefeld University, Neurocognition and Action – Research Group, Faculty of Psychology and Sport Science, PO-Box 100 131, 33501 Bielefeld, Germany. e-mail: heiko.lex@uni-bielefeld.de

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

displacement humans rely more on visual movement feedback.

The aim of the present study was to investigate sensorimotor adaptation performance with a distortion of the visual feedback in terms of a left-right reversal (i.e., horizontal displacement), and to measure the corresponding cognitive representations of movement directions when presented only in a visual mode. Thus, the study builds on the earlier investigation of Lex et al. (2012) in which the movement directions were presented in a proprioceptive-visual mode and aimed to examine the functional relationship between the cognitive representation and the adaptation behavior to visually presented movement directions.

Methods

Two experiments were conducted to investigate the functional relationship between cognitive representations of movement directions and subsequent sensorimotor adaptation behavior. Experiment 1 measured the cognitive representation of movement directions under the visual input modality. Experiment 2 assessed sensorimotor adaptation using a pointing task similar to the one previously used by Bock and Girgenrath (2006) integrating a different distortion of the visual feedback.

Participants

Forty-seven adults (M_{age} = 25.4 years, SD = 2.8 years; 24 women) participated in the study, with the majority of them being students at Bielefeld University. All participants declared themselves as right-handed, they were naive to the purpose of the experiment, and had normal or corrected-to-normal vision. The experiment consisted of a single session (starting with the measurement of the cognitive representation of movement directions), and experimental procedures were conducted in accordance with the 1964 Declaration of Helsinki. Participants signed an informed consent form prior to the experiment and received course credit for their research participation. All data was collected in a single session starting with the data acquisition of the measurement of cognitive representation of movement directions.

Sensorimotor Adaptation Task

Performance in the sensorimotor adaptation task was measured using a standard pointing experiment (Bock, 2005; Miall, Jenkinson, & Kulkarni, 2004). Participants were asked to execute center-out movements toward eight randomly appearing targets on a digitizer tablet. Movements were always performed from the center to the periphery of the screen and participants' hand locations on the digitizer tablet were displayed via a red cursor on the screen. After baseline recordings, visual feedback was distorted in terms of a left-right reversal in order to manipulate the normal relationship between sensory input and motor output.

Apparatus and Task. The apparatus and task used in the present experiment were identical to the sensorimotor adaptation task of Lex et al. (2012). Participants were seated in front of a monitor facing downward. The screen was visible through a tilted mirror that prevented vision of the own hands. Participants` right hand executed center-out movements from a center position to eight peripheral, equidistant target positions, randomly appearing on a digitizer tablet. To provide participants with real-time visual feedback of their hand movements, the hand position was displayed via a red cursor cross (8 mm in length and width) on the screen (similar to Miall, Jenkinson, & Kulkarni, 2004). Participants were asked to perform the movements with their right hand using an electronic pen, while the left hand was positioned and kept still beside the digitizer tablet. Movements were performed in episodes of 30 s, with a 5 s rest in between episodes (Bock, 2005; Bock & Girgenrath, 2006). The experiment started with three familiarization episodes, which were followed by two undistorted baseline conditions consisting of five episodes each. Baseline condition 1 (BL1) recorded participants' performance with veridical visual feedback of their movements. Baseline condition 2 (BL2) recorded the same movements than BL1, but without real-time visual feedback of the actual hand position. Instead, feedback of the cursor position was only provided when the cursor was within an arc radius of 10 mm around the center position of the screen to ensure participants were able to return to the starting position. The two BL conditions were followed by an adaptation phase (AP), in which participants were asked to perform the same movement task, but were presented with visual feedback that was distorted via a left-right reversal (i.e., mirrored along the mid-sagittal plane). The AP consisted of 30 episodes to ensure there was enough time to initiate a sensorimotor adaptation process. Subsequent to the AP participants were offered a 5-min break in which they were allowed to move around and relax. They continued with five episodes in the phase of persistence (PP) under distorted condition, but without real-time visual feedback of the movements.

Data Analysis. An initial angular error (IAE) was measured to determine participants' pointing performance. The IAE was computed between the direct target direction and initial hand direction for each pointing movement. The direct target direction was defined by the hand position at movement onset (i.e., center position) and the target location. The initial hand direction in contrast was defined by the hand position at movement onset (i.e., center position) and the hand position at first peak velocity with a minimum velocity of 30 mm/s. The minimum velocity threshold at movement onset was defined to ensure that initial small corrective adjustments (i.e., directly around the center position) were not considered within data analysis. Overall, the

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

IAE measure is largely unaffected by feedback-based corrective adjustments that occur during later stages of the pointing movement, in which participants slow down their movements and perform a winding path toward the target to ensure for successive movement performance. The mean IAE was calculated for all pointing movements within each episode. The mean adaptation performance of each episode was averaged into blocks of five episodes to judge participants' pointing performance (Bock & Girgenrath, 2006). Therefore, the blocks measuring pointing performance were constituted as BL1, BL2, AP1–AP6, and PP representing the mean pointing performance of five episodes each. An analysis of variance (ANOVA) with repeated measures and a simple contrast analysis were conducted to examine differences within the adaptation phase. Baseline performances were examined by a two-tailed *t* test.

Cognitive Representation of Movement Directions

The representation of movement directions was measured using the Cognitive Measurement of Represented Directions (C-MRD), an experimental setup used by Lex et al. (2012), and based on the methodological background of the Structural Dimensional Analysis of Motor Representations (SDA-M; Schack & Mechsner, 2006).

Apparatus and Task. The C-MRD was performed at the same table as the sensorimotor task. A standard monitor was placed in front of the participants and used to provide normal vision on the screen. Following the sensorimotor adaptation task, we used animated red fading movement dots (with a center-out movement direction) to measure cognitive representations of movement directions. The moving dots were depicted as animated gif files on the computer screen (see Figure 1), and moved into 12 different directions, spread evenly on a full circle every 30°. One of the 12 movement directions was presented in the upper part of the (horizontally split) screen in an anchoring position, and the remaining eleven movement conditions were successively and randomly presented in the lower part of the screen in a signifier position. The movement direction in the anchoring position remained repetitive on the screen, until it was compared with every other movement direction. Subsequent to that the next movement direction was displayed as well in the anchoring position, and compared with the remaining eleven movement directions. The procedure was repeated until each movement direction had been presented once in the anchoring position. Twelve movement directions were compared with each other, thus asking participants to make a total of 12 times 11 decisions, as the anchoring position was predefined as most similar to itself.

The task for the participants was to compare the movement direction in the anchoring position with that in the signifier position with regard to their similarity. More specifically participants were asked to decide whether or not the two presented movement directions seemed similar to them. Participants were instructed to make their decisions spontaneously, which was facilitated through a singular stimuli presentation, but no given time restrictions. Decisions were made by either pressing a plus button (similarity) on the left or a minus button (no similarity) on the right side of the screen. Participants' judgment was entirely based on a self-defined similarity criterion, and made with regard to their own representation of movement directions.

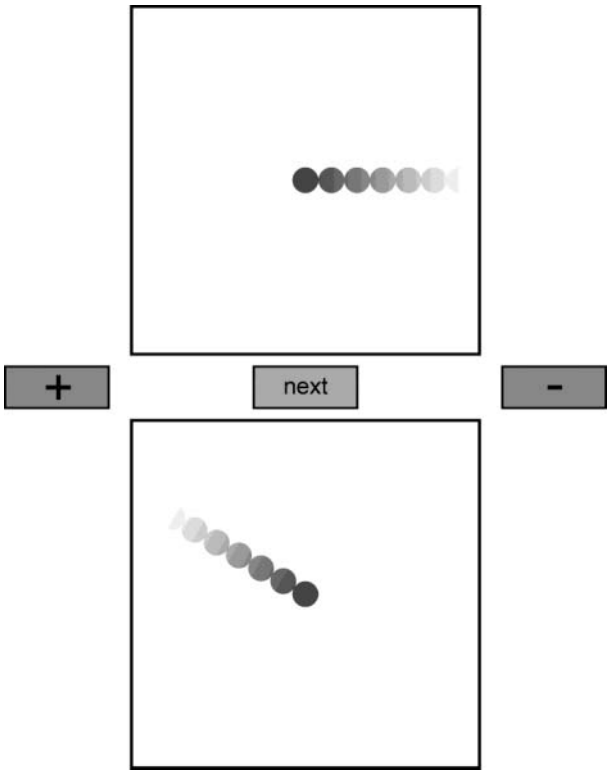


FIGURE 1. Cognitive Measurement of Represented Directions (C-MRD) data of cognitive representation of movement directions. When splitting procedure was started, the dot (colored in red) in the upper screen (anchoring position) moved into one movement direction (e.g. direction $4 = 90°$ straight to the right). After this one faded out, the dot in the lower screen (signifier position) moved into one of the other residual eleven movement directions (e.g. direction $11 = 300°$ to the upper left). When the participants decided for similarity they pressed the plus button (on the left), and for dissimilarity the minus button (on the right). The next movement direction appeared immediately the decisions. When the movement direction in anchoring position was compared with every other direction, the next button (in the center) was enabled, and the splitting procedure started again with a new direction in the anchoring position.

Data Analysis. The data analysis of participants' decisions in the C-MRD consisted of three steps (for more details on the method see Lex et al., 2012). The first step

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

consisted of the splitting procedure to log participants' decisions. Their decisions were transformed into an Euclidian distance matrix that represents the distances between the twelve movement directions. This matrix forms the basis for the second step. The second step used the Euclidian distance matrix to perform an unweighted average-linkage cluster analysis to elicit the cognitive representation of movement directions in the form of dendrograms. In the third step, the generated representation structures have been tested for structural homogeneity by an invariance measure between groups. The statistically suggested threshold for accepting invariance is set to $\lambda_{crit} = .68$ (Lander & Huth, 1999; Schack, 2011).

Representation of Movement Directions by Sensorimotor Adaptation Performance Level

The last analytic step combined the results of the sensorimotor adaptation task in dependence on the representation of movement directions. Therefore, the individual adaptation performance of each participant was quantified by an adaptation index A_k (identical to Lex et al., 2012). The adaptation index is described by the following equation:1

$$A_k = \frac{AP_1 - AP_6}{AP_1 - BL_1}$$

The index k represented the participant's indicator. $A_k = 1$ means a perfect adaptation back onto baseline level by the participant, whereas $A_k = 0$ indicates no adaptation at all (i.e., no changes in direction of distortion compared to undistorted baseline performance). Subsequently, all participants were sorted in descending order according to their adaptation index, and separated into three groups. The first one third represented the skilled adapters ($n = 16$), the second one third the average adapters ($n = 15$), and the last one third the poor adapters ($n = 16$). The group separation of the sensorimotor adaptation task (skilled, average, and poor adapters) was retained for the representation of movement directions. Therefore, participants' mean group dendrograms were calculated to reflect the corresponding cognitive representation of movement directions. The emerged group dendrograms were then tested for invariance.

Results

The IAE measured a participant's performance in the sensorimotor adaptation task. The results of all participants showed a mean IAE for BL1 of 3.17° ($SD = 1.7$) and for BL2 of 3.20° ($SD = 1.4$). A t test (two-tailed) revealed no differences between the baselines under different feedback conditions, $t(45) = -0.143$, $p = .887$. The mean IAE for AP1–AP6 were 33.42° ($SD = 10.5°$), 23.14° ($SD = 9.4°$), 17.62° ($SD = 8.9°$), 15.01° ($SD = 7.2°$), 14.38° ($SD = 8.6°$), and 12.89° ($SD = 7.4°$), respectively. An ANOVA for the adaptation phase revealed a main effect for adaptation phase, $F(4.006, 172.279) = 49.249$, $p < .001$, $\eta^2 = .534$. Mauchly's test revealed that the sphericity assumption was violated, $\chi^2(14) = 38.417$, $p < .001$. Therefore, the degrees of freedom were corrected by estimation of sphericity according to Greenhouse-Geisser ($\varepsilon = .801$). Accordingly, all participants adapted to the visual disturbance over the adaptation phase. A simple contrast analysis revealed successful adaptation to all phases against the first phase (all ps $< .001$), but adaptation gains decreased over time. The nonsignificant difference between the last adaptation phase (AP6) and the phase of persistence (PP), $t(45) = 0.938$, $p = .353$, revealed that participants' adaptation performance persisted over time for at least five minutes.

The individual adaptation performance of the whole adaptation process was defined by an adaptation index for each participant. All participants adapted to 0.66 ($SD = 0.26$) toward the visual distortion. The skilled adapters (GA) showed a mean adaptation index of 0.89 ($SD = 0.09$), the average adapters (AA) of 0.71 ($SD = 0.05$), and the poor adapters (PA) of 0.38 ($SD = 0.26$). Figure 2 shows the performance curves of the skilled, the average, and the poor adapters in the sensorimotor adaptation task (a) and the mean adaptation index of all groups.

In a last step the results of the sensorimotor adaptation task have been applied onto the results of the representation of movement directions. Therefore, the group separation generated from the adaptation index was used to define the groups of skilled, average, and poor adapters and their corresponding cognitive representation of movement directions. Figure 3 shows the evolved cluster structures from the C-MRD of all groups. Skilled adapters' cognitive representation of movement directions included between two and three neighboring movement directions in each cluster. The evolved clusters integrated the cardinal axes in the horizontal and sagittal plane (i.e., the movement directions 1, 4, 7, and 10). Average adapters cognitive representation of movement directions showed four distinct clusters, but the movement directions 1, 7, and 8 are singled out. The cognitive representation of movement directions of the poor adapters included two neighboring movement directions per cluster. But in here, all cardinal movement directions representing the main axes in the horizontal and sagittal plane (i.e., 1, 4, 7, and 10) are singled out in their respective cognitive representation of movement directions.

The evolved mean cluster structures of all three groups have been further analyzed to compare the resultant cognitive representation of movement directions of both groups for structural homogeneity with each other. The results of the invariance measure for the cognitive representations of movement directions showed no invariance between the groups (i.e., skilled to average adapters $\lambda = .40$, average to poor adapters $\lambda = .53$, and skilled to poor adapters $\lambda = .38$). Therefore, all groups exhibited a completely distinct cognitive representation of movement directions measured under visual stimulus presentation with regard to the sensorimotor

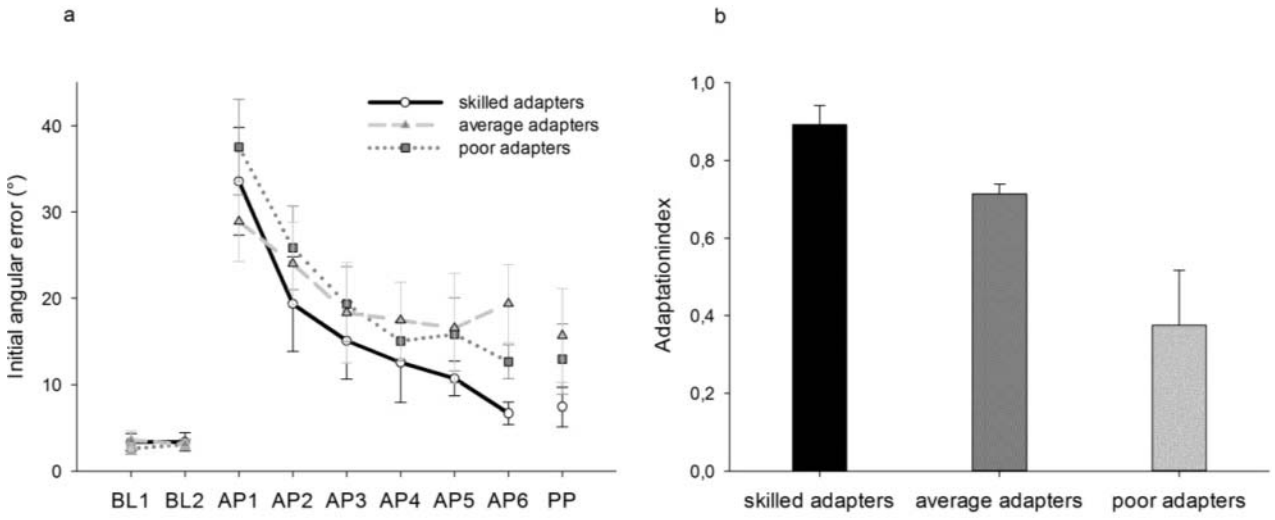


FIGURE 2. (a) Pointing performance over the phases of the skilled, average, and poor adapters in the sensorimotor adaptation task with a distortion of the visual feedback in terms of a left-right reversal. Recorded are two different baseline phases. Baseline 1 (BL1) included visual movement feedback, and in BL2 visual movement feedback was occluded. During the adaptation phases (AP1–AP6) and the phase of persistence (PP) visual feedback was distorted by a left-right reversal. In the PP visual feedback was occluded as in BL2. The *y*-axis represents the initial angular error α between the direct target direction and initial hand direction in angular degrees. The error bars indicate the 95% CI. (b) The adaptation index of the sensorimotor adaptation task. The vertical bars show the mean adaptation index for all three groups. The error bars represent the 95% CI.

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

adaptation performance. Skilled adapters possessed a global representation of movement directions (integrating the movement directions of the cardinal axes), whereas poor adapters possessed a local representation of movement directions (separating the movement directions of the cardinal axes).

An interesting side effect is observable in the cognitive representation of movement directions in skilled and poor adapters. Without regard to the statistical suggested threshold (d_{crit}) the cluster analysis connects all movement directions with each other. Two major direction-sensitive blocks were identified for all groups. Hence, the skilled adapters differentiated between movement directions on the left (8 to 10) and the right hand side (1 to 7). The average adapters' possessed a comparable representation structure (2 to 7, and 8 to 1) separating left and right. However, the poor adapters' representation indicated two direction-sensitive blocks connecting up- (10 to 3) and downward (4 to 9) directions.

Discussion

The results of the experiments provided further evidence for the impact of cognitive representations of movement directions on sensorimotor adaptation performance. Our results suggested that a global cognitive representation of movement directions is advantageous in adaptation tasks with a distortion of the visual feedback in terms of a left-right reversal. Thus, it is disadvantageous in such an adaptation task when humans possess a local representation of movement directions. Identically to a previous study conducted by Lex et al. (2012), the local representation of movement directions of poor adapters assembled neighboring movement directions. The peculiarity in the representation of movement directions of poor adapters was the extinction of the cardinal axes. This extinction led to a performance decrease in the sensorimotor adaptation with a distortion of the visual feedback. In contrast, the global representation of movement directions within skilled adapters led to a better performance in an adaptation task with a distortion of the visual feedback along the sagittal axis. It seems that comparable mechanisms are triggered in the activation of responsible cognitive representations of movement directions and in sensorimotor adaptation tasks. For example, the proportion of the impact of representations of movement directions on sensorimotor adaptation performance relies on the specificities of the distortion in the adaptation task. Van Beers et al. (2002) found evidence that the adaptation performance is dominated by proprioceptive movement feedback for azimuthally distortion (leftward), and dominated by visual movement feedback for distortions in depth (forward). Subsidiary to previous experiments conducted by Lex et al. (2012), it was found that adaptation performance depends on whether cognitive representations are triggered by visual or visual-proprioceptive presented movement directions. The sensory input

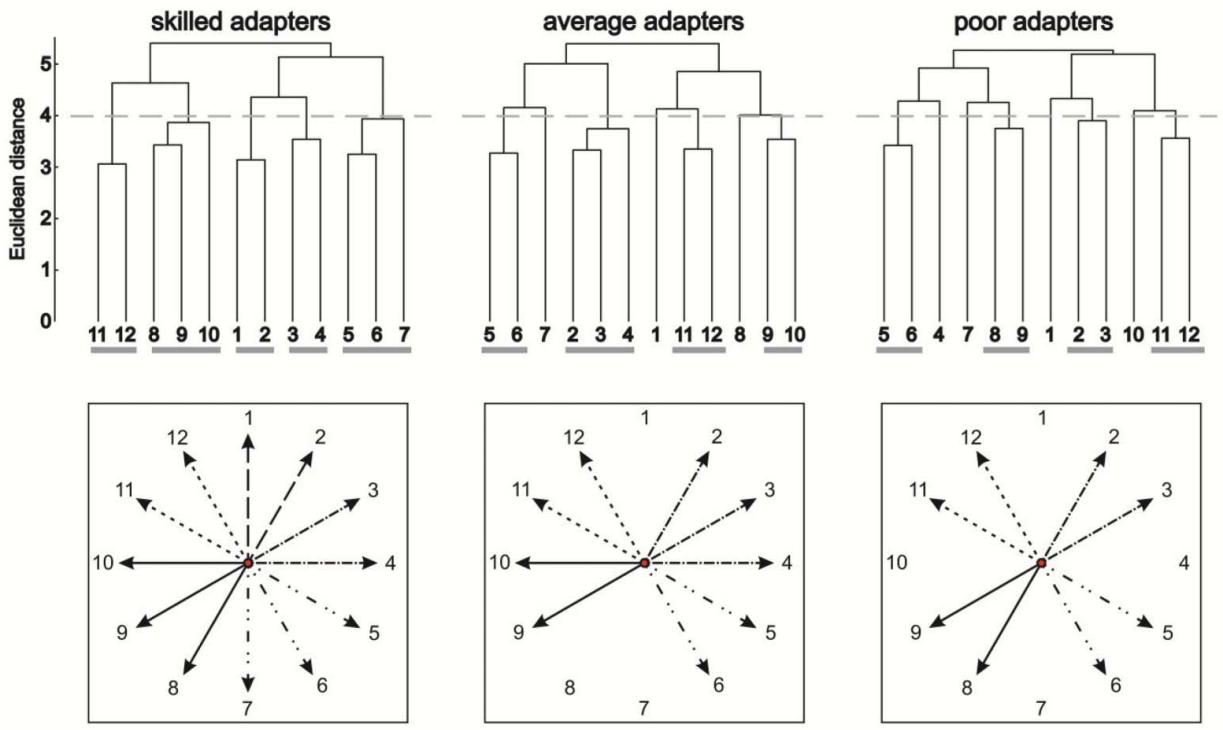


FIGURE 3. The dendrogram in the upper part shows the average cluster structure of all three groups. The numbers at the bottom of each dendrogram reflect the corresponding movement direction in clockwise order starting with one in the straight upright position. The numbers at *y*-axis reflect the corresponding Euclidian distances for the conjunctions in the dendrogram. The grey dashed line indicates an estimated critical Euclidian distance ($d_{crit} = 3.987$) at which all branches of the dendrogram were cut off. The critical Euclidian distance is estimated by the application of an error probability of $p = .025$. All movement directions connected below that critical distance can be considered as integrated in one cluster. On the contrary, all movement directions connected above the critical distance are not integrated into a distinct cluster. The evolved clusters are marked by solid gray bars at the bottom. The bottom of Figure 3 displays the resulting cluster structures depicted as directional arrows. Arrows depicted in the identical manner (i.e. solid, dotted, or dashed) represent a corresponding cluster in the dendrograms.

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

modalities (i.e., proprioceptive-visual or visual only) of presented movement directions influenced the cognitive representation, and a main tendency was revealed. This suggests that humans possess a general cognitive representation of movement directions aligned to global (i.e., cardinal directions) or local (i.e., neighboring directions) representations of movement directions.

The adaptation toward rotated visual movement feedback can be described as direction sensitive. The direction sensitivity toward different target position has been explained by different functional modules, each pertinent to a narrow range of the response direction (Werner & Bock, 2010). In addition, a separate processing of extent and directional errors in reaching movements has been suggested, which might be planned as hand-centered vectors, whose extent and direction are established via learning a scaling factor and a reference axes (Krakauer, Pine, Ghilardi, & Ghez, 2000). Furthermore, Werner and Bock (2010) indicated that cognitive processes allowing adaptation toward reversed feedback are similar to rotated visual feedback. It has been predicted that these processes are able to change a global internal representation of space or rather multiple directions-specific modules. Based on the results of the present study, however, we provide a different argument. Our data suggests that the cognitive representation of movement directions (measured before the sensorimotor adaptation) can be interpreted as a reference frame within human motor memory. Such a cognitive reference frame influences the whole adaptation performance toward reversed visual feedback. Hence, it can be interpreted as a direction-specific and overarching module in human motor memory (comparable to Tanaka, Worringham, & Kerr, 2009). However, further research is needed to investigate the influence of the cognitive representation of movement directions on adaptation toward rotated visual feedback to strengthen such an argument.

Further evidence is provided by experiments where the participants adapted toward different distortions (i.e.,

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014

visual and mechanical) with normal or impaired proprioceptive feedback. The results showed that intact proprioception is needed for adaptation toward a mechanical distortion, but not toward a visual distortion. Both sensory modalities seemed to be independent from each other (Pipereit, Bock, & Vercher, 2006). In accordance to the present study it can be assumed that cognitive structures, similar to representations of movement directions, are involved in adaptation tasks. Moreover, there is additional neurophysiologic evidence for the existence of a movement related system, which encodes movement directions in the motor cortex. Comparable neuronal activity was measured in the motor cortex, when reaching movements were executed in specific movement directions (Georgopoulos, 2000; Georgopoulos, Caminiti, Kalaska, & Massey, 1983; Georgopoulos, Kalaska, Caminiti, & Massey, 1982; Georgopoulos, Schwartz, & Kettner, 1986). Thus, the cognitive representation of movement directions can be considered as a cognitive structure, which is relevant in direction sensitive sensorimotor adaptation tasks. It remains speculative that cognitive representations of movement directions will be activated during other direction sensitive complex motor actions. More research needs to be conducted to verify such a bold idea.

Altogether, it can be proposed that the cognitive representation of movement directions may be considered as an indicator for measuring adaptation performance in pointing tasks with a visual disturbance in terms of a left-right reversal. Moreover, it can be concluded that the representation structure seems to be a valid predictor for sensorimotor adaptation performance.

ACKNOWLEDGMENTS

The authors thank Tino Stöckel for his very helpful comments and suggestions on former versions of the present article.

FUNDING

Heiko Lex gratefully acknowledges the financial support from Honda Research Institute Europe for the project "Cognitive planning and motor adaptation in manual action."

REFERENCES

Abeele, S., & Bock, O. (2001). Mechanisms for sensorimotor adaptation to rotated visual input. *Experimental Brain Research*, *139*, 248–253. doi:10.1007/s002210100768

Bock, O. (2005). Components of sensorimotor adaptation in young and elderly subjects. *Experimental Brain Research*, *160*, 259–263. doi:10.1007/s00221-004-2133-5

Bock, O., & Girgenrath, M. (2006). Relationship between sensorimotor adaptation and cognitive functions in younger and older subjects. *Experimental Brain Research*, *169*, 400–406. doi:10.1007/s00221-005-0153-4

Bock, O., Schneider, S., & Bloomberg, J. (2001). Conditions for interference versus facilitation during sequential sensorimotor adaptation. *Experimental Brain Research*, *138*, 359–365. doi:10.1007/s002210100704

Ferrel, C., Bard, C., & Fleury, M. (2001). Coordination in childhood: modifications of visuomotor representations in 6-to-11-year-old children. *Experimental Brain Research*, *138*, 313–321. doi:10.1007/s002210100697

Georgopoulos, A. P. (2000). Neural aspects of cognitive motor control. *Current Opinion in Neurobiology*, *10*, 238–241. doi:10.1016/S0959-4388(00)00072-6

Georgopoulos, A. P., Caminiti, R., Kalaska, J. F., & Massey, J. T. (1983). Spatial coding of movement: A hypothesis concerning the coding of movement direction by motor cortical populations. *Experimental Brain Research*, *7*(Supplement), 327–336.

Georgopoulos, A. P., Kalaska, J. F., Caminiti, R., & Massey, J. T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *The Journal of Neuroscience*, *2*, 1527–1537.

Georgopoulos, A. P., Schwartz, A. B., & Kettner, R. E. (1986). Neuronal population coding of movement direction. *Science*, *233*, 1416–1419.

Ingram, H. A., van Donkelaar, P., Cole, J., Vercher, J. L., Gauthier, G. M., & Miall, R. C. (2000). The role of proprioception and attention in a visuomotor adaptation task. *Experimental Brain Research*, *132*, 114–126. doi:10.1007/s002219900322

Krakauer, J. W., Pine, Z. M., Ghilardi, M. F., & Ghez, C. (2000). Learning of visuomotor transformations for vectorial planning of reaching trajectories. *Journal of Neuroscience*, *20*, 8916–8924.

Lander, H. J., & Huth, M. (Eds.). (1999). *Ein Verfahren zur Ermittlung der Strukturierung und Dimensionierung begrifflich repräsentierten Wissens im Langzeitgedächtnis* [A method to ascertain the structure and the dimensioning of conceptually represented knowledge in long-term memory]. Leipzig, Germany: Universitätsverlag.

Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. *Experimental Brain Research*, *223*, 457–467. doi:10.1007/s00221-012-3273-7

Mazzoni, P., & Krakauer, J. W. (2006). An implicit plan overrides an explicit strategy during visuomotor adaptation. *The Journal of Neuroscience*, *26*, 3642–3645. doi:10.1523/JNEUROSCI.5317-05.2006

Miall, R. C., Jenkinson, N., & Kulkarni, K. (2004). Adaptation to rotated visual feedback: a re-examination of motor interference. *Experimental Brain Research*, *154*, 201–210. doi:10.1007/s00221-003-1630-2

Pipereit, K., Bock, O., & Vercher, J. L. (2006). The contribution of proprioceptive feedback to sensorimotor adaptation. *Experimental Brain Research*, *174*, 45–52. doi:10.1007/s00221-006-0417-7

Redding, G. M., & Wallace, B. (1996). Adaptive spatial alignment and strategic perceptual-motor control. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 379–394. doi:10.1037/0096-1523.22.2.379

Schack, T. (2011). Measuring mental representations. In G. Tenenbaum, R. C. Eklund, & A. Kamata (Eds.), *Handbook of Measurement in Sport and Exercise Psychology* (Vol. 1, pp. 203–214). Champaign, IL: Human Kinetics.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. *Neuroscience Letters*, *391*, 77–81. doi:10.1016/j.neulet.2005.10.009

Tanaka, H., Worringham, C., & Kerr, G. (2009). Contributions of vision–proprioception interactions to the estimation of time-varying hand and target locations. *Experimental Brain Research*, *195*, 371–382. doi:10.1007/s00221-009-1798-1

Van Beers, R. J., Wolpert, D. M., & Haggard, P. (2002). When feeling is more important than seeing in sensorimotor adaptation. *Current Biology*, *12*, 834–837. doi:10.1016/S0960-9822(02)00836-9

Werner, S., & Bock, O. (2010). Mechanisms for visuomotor adaptation to left-right reversed vision. *Human Movement Science*, *29*, 172–178. doi:10.1016/j.humov.2010.02.004

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269*(5232), 1880–1882. doi:10.1126/science.756993

Received January 22, 2014
Revised March 31, 2014
Accepted April 28, 2014

Downloaded by [Universitaetsbibliothek Bielefeld] at 02:50 13 September 2014