Watching Gestures during Learning about Movements with Dynamic Visualization Activates the Human Mirror Neuron System: A fNIRS Study

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Abstract

This study investigates whether viewing human gestures facilitates learning about non-human biological movements and whether correspondence between gesture and to-be-learned movement is superior to non-correspondence. Functional near-infrared-spectroscopy was used to address whether gestures activate the human mirror-neuron-system (hMNS) and whether this activation mediates the facilitation of learning. During learning participants viewed triples of visualizations (animation – gesture video – animation). Results showed that for low-visuospatial-ability learners corresponding gestures led to higher cortical activation in the inferior-frontal cortex (part of the hMNS) and better learning outcomes, whereas for high-visuospatial-ability learners the type of gesture had no influence. Furthermore, results showed that – if presented with non-corresponding gestures – only low-visuospatial-ability learners who activated their inferior-parietal cortex (also part of the hMNS), improve their learning. Thus, activating the hMNS facilitates learning about movements and stimulating the hMNS via gestures seems to be an adequate instructional strategy to enhance learning with dynamic visualizations for low-visuospatial-ability learners.

Keywords: Learning about movements; dynamic visualizations; human mirror-neuron-system; gestures; functional near-infrared-spectroscopy.

Learning about Movements with Dynamic Visualizations

Many contents in the Natural Sciences as well as in other domains, such as different sport disciplines or scene perception, comprise the understanding of changes in space over time. Dynamic visualizations can easily depict such changes and they may be particularly suited for instructional purposes if these changes do not occur in a discrete or linear way, but rather involve more complex continuous aspects (e.g., acceleration). However, they were not always superior to static visualizations to convey dynamic information (e.g., Imhof et al., 2012). Thus, it is crucial to understand when and for whom dynamic visualizations are beneficial to use them effectively and to exploit their potential for learning. Until now, research on the instructional use of dynamic visualizations has yielded rather heterogeneous results: Not only design factors and individual learner characteristics, but also context factors, such as, the knowledge domain, task requirements, or additional instructional support, influence the effectiveness of dynamic visualizations (e.g., Höffler & Leutner, 2007; Lowe, Schnotz, & Rasch, 2011; Tversky, Morrison, & Bétrancourt, 2002). These context factors have become a focus of research on dynamic visualizations.

Learning with Gestures

One idea on how to support learning about movements with dynamic visualizations that is based on the embodied cognition approach and proposed by De Koning and Tabbers (2011) is the active and passive use of gesture. Empirically, Hegarty et al. (2005) showed that gestures are naturally used to express movements of depicted components and thereby also the depicted processes in mental animation problems. Moreover, it has already been shown that the production of gestures during learning is beneficial for acquiring knowledge about different scientific topics and spatial problem solving (e.g., Chu & Kita, 2011; Cook & Goldin-Meadow, 2006; Scheiter et al., 2012). However, learners can either produce gestures on their own or they can perceive gestures that are performed by others. In line with the proposal of De Koning and Tabbers (2011), it is also beneficial for learning to perceive gestures that illustrate the depicted contents, for instance, performed by teachers (e.g., Valenzeno, Alibali, & Klatzky, 2003).

Underlying this gesture watching effect might be the activation of brain areas (i.e., the human mirror-neuron-system [hMNS]; Fogassi & Ferrari, 2011; Rizzolatti & Craighero, 2004) that are typically used to observe, understand and imitate the actions of other persons. In a related line of research, a current hypothesis that has recently received considerable attention (e.g., Ayres et al., 2009; Van Gog et al., 2009) is that the stimulation and involvement of this hMNS might be beneficial for learning about complex continuous aspects with dynamic visualizations. The hMNS is typically activated by human movements, but may be more generally used to also represent other biological or even non-biological movements, if the observer is able to anthropomorphize

these movements (cf. De Koning & Tabbers, 2011; Engel et al., 2008). Thus, in the domain of learning about biological movements, one effective instructional strategy to activate the hMNS might be to show learners not only the to-be-learned movements via dynamic visualizations, but also gestures displaying the to-be-learned dynamics in order to trigger an anthropomorphized encoding. Hence, only showing gestures that map onto the to-be-learned movements should benefit learning about those movements.

This study addresses whether perceiving gestures in addition to dynamic visualizations is also beneficial for learning. Moreover, to investigate the role of the hMNS, the underlying cognitive processes during learning were investigated with neurophysiological methods in this study (i.e., functional near-infrared-spectroscopy [fNIRS]). Until now, to the best of our knowledge, there is no direct test of the assumption that learners' ability to recruit their hMNS during processing dynamic visualizations may influence the effectiveness of the visualizations. Moreover, it still has not been investigated whether hMNS activation can be induced by gesture-based interventions and then transferred to non-human movements because of mapping processes. This approach might easily facilitate the understanding of complex dynamic phenomena by implementing embodied visualizations that activate specific brain areas into instructional materials.

Learners' Visuospatial Ability

Beyond context factors also individual learner characteristics may play a role during learning about biological movements. Because processing continuous changes requires visuospatial ability (cf. Hegarty, 1992), it is likely that learners' visuospatial ability will determine how much the learners profit from visualizations (cf. Hegarty & Waller, 2005). Often the continuous processes do not occur only in two-dimensional but rather in three-dimensional space. Thus not only visual, but also spatial aspects are important. Previous research on visuospatial ability has revealed two important results, namely that (a) learners with higher visuospatial ability outperform learners with lower visuospatial ability during learning with visualizations (see Höffler, 2010, for a meta-analysis) and moreover, there is some evidence, that (b) visuospatial ability may moderate the effectiveness of learning with different visualization formats. Higher visuospatial ability may compensate for "poor" instructions (i.e., in our case unrelated non-corresponding gestures, cf. methods section), whereas learners with lower visuospatial ability suffer from such instructions (cf. ability-as-compensator hypothesis; e.g., Hays, 1996; Hegarty & Kriz, 2008; Höffler, 2010).

Research Questions and Hypotheses

This study addressed by using neurophysiological methods (i.e., functional near-infrared-spectroscopy [fNIRS], which is a non-intrusive approach to gather data about cortical activation of humans) the research question whether the hMNS is activated during viewing gestures and whether the viewing of these gestures is helpful for learning about biological movements because learners map the human movements to the non-human biological movements.

However, maybe solely the circumstance that learners see a human during learning activates the hMNS and is thus sufficient to facilitate learning about biological motions. In other words, it might be also helpful for learners to see gestures that have nothing to do with the to-be-learned content. Thus, this study investigated whether viewing gestures that correspond to the to-be-learned non-human movements facilitate learning about these movements better than unrelated non-corresponding gestures. Additionally, the moderating role of learners' visuospatial ability was addressed. Furthermore, this study tested whether the activation of the MNS mediates the facilitation of learning.

We hypothesize that viewing corresponding gestures facilitates learning more than viewing unrelated non-corresponding gestures. This might be particularly true for low-visuospatial-ability learners, whereas high-visuospatial-ability learners might not need this type of anthropomorphization to learn about the depicted dynamic processes (cf., ability-as-compensator hypothesis; e.g., Höffler, 2010). Moreover, we hypothesize that learners differ with regard to recruiting the hMNS for processing and that higher hMNS activation is associated with better learning outcomes than lower hMNS activation. This might again be particularly true for low-visuospatial-ability learners, as they do not have available this ability to compensate for such a hMNS actication.

Methods

Participants and Design

Forty-five university students (M = 24.98 years, SD = 4.57; 31 females) were asked to learn how to classify different fish according to their movements based on visualizations that illustrated four different movement patterns of fish. For each movement pattern the participants saw three visualizations: Firstly, they saw an animation of the specific movement pattern. Secondly, they saw a video of a person performing gestures with his hands and arms. These gestures either did correspond or did not correspond (i.e., were unrelated) to the fish movement patterns. Therefore, at this point the experimental manipulation with the between-subjects factor *type of gesture* took place. Thirdly, the learners saw the initial fish animation again.

An expert regarding fish movements performed the gestures. For the corresponding gestures this expert was instructed to display with his hands and arms representations of the respective movements as clearly as possible (see figure 1 left). For the non-corresponding gestures the expert was instructed to perform gestures with his hands and arms that were unrelated to the fish movement patterns (i.e., waving, circulating the forearms around each other, drumming, and pointing, see figure 1 right).

Each visualization was depicted for 30 s and was followed by pauses of 30 s (black screen) between all

visualizations. The learners were instructed to relax in these pauses. In the pauses, the activations of the brain areas of interest are supposed to decay to the baseline level before the next visualization was displayed.
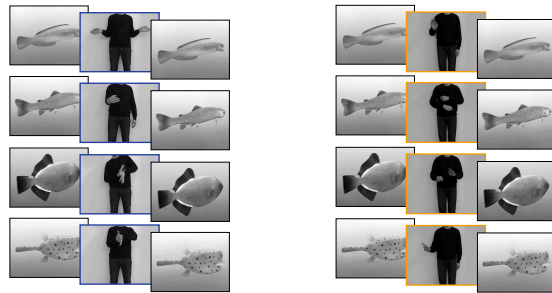

Figure 1: Learning visualizations in triples: corresponding gestures (left) and non-corresponding gestures (right).

Materials

Participants had to learn to discriminate four different patterns of fish movements. These movement patterns differ in terms of the body parts that generate propulsion (i.e., the body itself or several fins) and also in the manner of how these body parts move in the three-dimensional space (i.e. different wave-like or paddle-like movements). The four different movement patterns were: 1. undulation of the body; 2. undulation of the dorsal and anal fins; 3. oscillation of the dorsal and anal fins (and undulation of the pectoral fins); and 4. oscillation of the pectoral fins. One major challenge in identifying these movement patterns is that fish may deploy other movements in addition (e.g., to navigate), that can easily be confused with movements used for propulsion in another movement pattern.

Animations were rendered based on typical fish performing the four movement patterns. These animations were standardized in terms of the perspective, background, position in the frame, and the swimming direction of the fish. Moreover, in these deliberately designed visualizations, we were able to only show the movements performed for propulsion and omit other irrelevant movements. Beside that, the depicted movements were highly realistic, thus representing the movements of real fish adequately. The movement cycles of the movement patterns were presented in loops in the animations (30 s per movement pattern, 25 fps, size: 640 x 480 pixels) in the center of the screen.

For each movement pattern, videos of an expert regarding to fish movements were recorded who performed either a corresponding or a non-corresponding gesture. These gestures were presented in the respective conditions in loops in the videos (30 s per movement pattern, 25 frames per s, size: 640 x 480 pixels) in the center of the screen. The presentation of all visualizations was system-controlled.

Measures

Learning Outcomes To assess learning outcomes, a movement pattern classification test was administered. This test comprised 21 dynamic multiple-choice items consisting of underwater videos of real fish performing one of the four to-be-learned movement patterns. To choose for each item the kind of movement pattern that was depicted, learners had to identify the body parts relevant for propulsion and their way of moving. Each item was presented 7 s to the participants and immediately afterwards they had 3 s time to choose the correct answer by pressing a corresponding button. The possible answers were indicated as static screenshots from the learning animations of the four movement patterns. Each item was awarded one point for the correct answer (max. 21 points). The test items were presented in blocks of 30 s so that 3 items were grouped together. Pauses of 30 s (black screen) followed each block.

Learners' Visuospatial Ability Learners' visuospatial ability was assessed with a short version of the paper folding test (PFT, Ekstrom et al., 1976). This test measures the ability to form representations of "object location, movement, spatial relationships, and transformations" (Blazhenkova & Kozhevnikov, 2009, p. 640) and thus is well suited to cover the domain of fish movements. The short version of the PFT consists of ten multiple-choice items, where participants have to choose the correct answer out of five options. The stimuli are depictions of stepwise folded papers that were punched in the folded state, whereas the answer options depict the punches of various unfolded papers with the punches being either in the correct or incorrect positions. A maximum of three minutes is assigned to work on the items, and each correct answer is worth one point (max. 10 points).

Cortical Activation During viewing the gestures in the learning phase, cortical activation was conducted via fNIRS measurements with an ETG-4000 (Hitachi). As probe set we used a 2x22 channel array, that was placed over the fronto-temporo-parietal regions centered at the T3-T4 and C3-C4 positions (not exactly terminating on these positions because of the fixed interoptode distances) according to the standard locations of the 10-20 system. Changes of absorbed near-infrared light were transformed into relative concentration changes of oxygenated (O_2Hb) and deoxygenated haemoglobin (HHb). Local increases of O_2Hb as well as decreases of HHb are indicators of cortical activity (Obrig & Villringer, 2003).

Procedure

Participants were tested individually. They first received a printed overview in which they were informed about the procedure on the different parts of the study. Subsequently, they had to answer the PFT and a demographic questionnaire. Subsequently, the fNIRS probe set was placed on the scalp of the participants and adjusted with the help of the experimenter. Then, the learning phase started and the computer-based learning materials were presented. For each of the four to-be-learned movement patterns learners were presented with the triples of visualizations

(fish animation – gesture video – fish animation). In the learning phase the experimental manipulation took place. Learners saw either the corresponding or the non-corresponding gestures. Following the learning phase (12 min) learners performed a filler task (8 min), in which they listened to music. Subsequently, learners completed the movement classification test (8 min). To answer the test items participants were instructed to put both their forefingers and both their middle fingers on predefined keys. These keys were labeled with screenshots from the corresponding fish animations on the screen. In total, a single experimental session lasted approx. 50 minutes.

Results

Learning Outcomes

To analyze learning outcomes we conducted a multiple regression analysis with the categorical predictor *type of gesture* and the continuous predictor *learners' visuospatial ability*. We had to exclude four participants because of technical reasons (data loss) resulting in a total number of 41 participants in this analysis. Further, we had to exclude eight test items from the learning outcome measure, because participants answered them with a response rate of more than 95 %. The reliability analysis of the remaining 13 test items achieved a good to excellent cronbach's α of .85.

For learning outcomes the predictors in the regression analysis explained a significant portion of variance (p = .01). Results showed no effect of type of gesture on learning outcomes (p = .41, ns), whereas there was an effect for learners' visuospatial ability on learning outcomes (p = .04). This effect has to be interpreted in terms of the significant interaction between type of gesture and learners' visuospatial ability on learning outcomes (p = .04; figure 2).
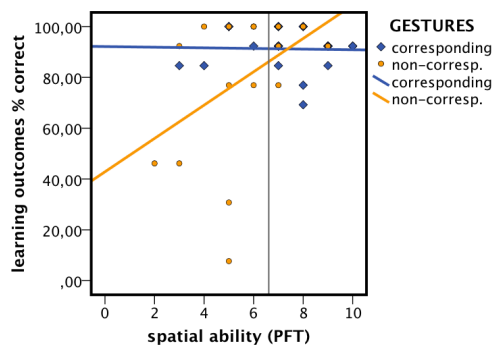

Figure 2. Interaction between learners' visuospatial ability and type of gesture on learning outcomes.

This interaction was resolved by a simple slopes analysis (cf. Aiken & West, 1991). It revealed that for participants with high visuospatial ability (defined as one standard deviation above the sample mean) the type of gesture had no influence on learning outcomes (p = .34, ns). As expected, for participants with low visuospatial ability (defined as one standard deviation below the sample mean) corresponding

gestures were better for learning than non-corresponding gestures (p = .04). Thus, the corresponding gestures are beneficial for low-visuospatial-ability learners.

Cortical Activation

To analyze the cortical activation we defined two regions of interest (ROIs) on the left hemisphere for the hMNS among the respective channels. The two ROIs were the left inferior-frontal cortex (IFC) and the left inferior-parietal cortex (IPC, cf. figure 3). To analyze cortical activation we conducted two multiple regression analyses with the predictors *type of gesture* and *learners' visuospatial ability*. We had to exclude additional eight participants from these analyses because the data quality of these participants was too poor resulting in a total number of 33 participants in these analyses. For cortical activation on IPC the predictors in the regression analysis did not explain a significant portion of variance (p = .96, ns).
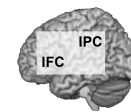

Figure 3. Spatial arrangement of the left probeset.

For cortical activation on IFC the predictors in the regression analysis explained a significant portion of variance (p < .001). Results showed an effect of type of gesture on IFC activation (p < .001) and an effect for learners' visuospatial ability on IFC activation (p < .001). These effects have to be interpreted in terms of the significant interaction between type of gesture and learners' visuospatial ability on IFC activation (p < .01; see figure 4).
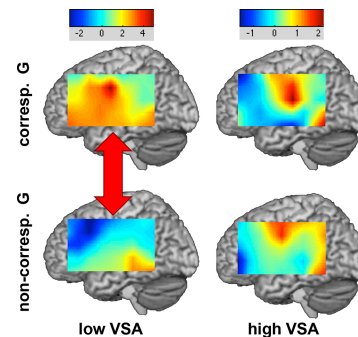

Figure 4. Effects of type of gesture (G) and learners' visuospatial activities (VSA) on cortical activation (left).

Again a simple slopes analysis was conducted (cf. Aiken & West, 1991). It revealed that for participants with high visuospatial ability (defined as one standard deviation above the sample mean) the type of gesture had no influence on IFC activation (p = .14, ns). For participants with low visuospatial ability (defined as one standard deviation below the sample mean) corresponding gestures resulted in a higher IFC activation than non-corresponding gestures (p <

.001). Thus, the corresponding gestures helped low-visuospatial-ability learners to activate the hMNS in terms of IFC activation.

Effects of Cortical Activation on Learning Outcomes

Finally, to address the question whether higher hMNS activation is directly associated with better learning outcomes, we conducted two multiple regression analyses with the three predictors *type of gesture*, *learners' visuospatial ability* and cortical activation in terms of *IFC activation* or *IPC activation* respectively.

For learning outcomes the predictors in the regression analysis with IFC activation did not explain a significant portion of variance ($p = .12$, ns). Interestingly, the predictors in the regression analysis with IPC activation did explain a significant portion of variance for learning outcomes ($p < .01$). There was a three-way interaction between the predictors type of gesture, learners' visuospatial ability, and IPC activation on learning outcomes ($p = .03$; see figure 5).
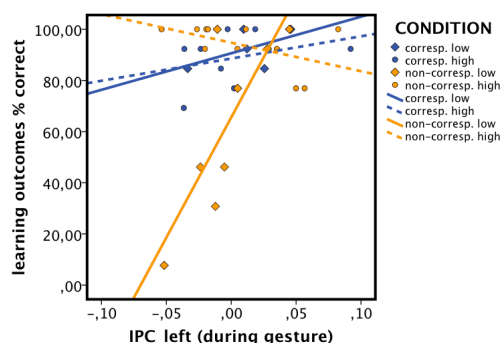

Figure 5. Three-way interaction between type of gesture, learners' visuospatial ability, and IPC activation on learning outcomes.

This triple interaction was resolved by simple slopes analyses (cf. Aiken & West, 1991). Firstly, this approach revealed that for learners who saw corresponding gestures there was no two-way interaction between participants' visuospatial ability and IPC activation ($p = .59$, ns). The following simple slopes analyses revealed that IPC activation did not predict learning outcomes for learners who saw corresponding gestures: neither for high-visuospatial-ability learners ($p = .47$, ns), nor for low-visuospatial-ability learners ($p = .40$, ns). However, for learners who saw non-corresponding gestures there was an interaction between participants' visuospatial ability and IPC activation ($p < .01$). We further resolved this two-way interaction between participants' visuospatial ability and IPC activation for learners who saw non-corresponding gestures. The simple slopes analyses revealed that in the group of learners who saw non-corresponding gestures IPC activation negatively predicted learning outcomes for high-visuospatial-ability learners ($p = .04$), whereas for low-visuospatial-ability learners IPC activation positively

predicted learning outcomes ($p = .001$). Thus, for learners who saw non-corresponding gestures, but have had high visuospatial abilities at their disposal IPC activation is detrimental for learning. However, for learners who did neither have corresponding gestures nor high visuospatial abilities at their disposal, activation of their hMNS in terms of the IPC during processing the unrelated non-corresponding gesture improves their learning.

Discussion

This study tested whether viewing gestures performed by others is helpful for learning about non-human movements and whether these gestures stimulate anthropomorphization via an activation of the hMNS. The anthropomorphization is stimulated by an external video and is not accomplished by the learners on their own. Our results showed that viewing corresponding gestures activated the hMNS particularly for low-visuospatial-ability learners. These learners achieved the same learning outcomes as high-visuospatial-ability learners. Low-visuospatial-ability learners seem to profit from being demonstrated a connection between non-human biological movements and movements of the human body that correspond to these movements. Thus, learning about biological movements can be facilitated by gesture-based interventions activating parts of the hMNS: Gestures that correspond to the to-be-learned movements and activate the inferior-frontal cortex (IFC). This activation seems to compensate missing viusospatial ability.

Furthermore, our results indicate another way of improving learning about biological movements: When looking at participants who neither have high visuospatial ability, nor received the benefit of viewing corresponding gestures, – namely, the group of low-visuospatial-ability learners who processed non-corresponding gestures – the result pattern was rather heterogeneous: Only participants who activated another part of the hMNS (i.e., the inferior-parietal cortex [IPC]) were able to dramatically improve their learning, whereas participants who did not activate this area achieved only poor results. This indicates that the activation of the inferior-parietal cortex helps participants to learn about biological movements, particularly if they have no access to other facilitating factors. In line with this reasoning, learners who have available two facilitating factors, namely high visuo-spatial abilities and an activation of the IPC, performed worse when they saw non-corresponding gestures. In this case, the two facilitators might compete and interfere with each other resulting in inferior learning outcomes. Nevertheless, higher hMNS activation is associated with better learning outcomes – at least for low-visuospatial-ability learners: for IFC activation it seems that there is a rather stepwise connection in that a certain value has to be reached, whereas for IPC activation it seems that it follows the more activation the better learning.

Stimulating the hMNS by means of gestures seems to be a promising strategy to enhance learning with dynamic visualizations for low-visuospatial-ability learners because this intervention leads to higher activation in their IFC as

part of the hMNS. However, further research needs to replicate these findings with a larger sample size and continue to disentangle the effects of this study. Particularly, our findings have to be replicated with other examples of gestures in different domains, as gestures about fish movements might not be a typical example of gestures. Furthermore, it is very important to investigate how the activation of the IPC can also be fostered by instructions.

Furthermore, gesture-based instructions that support anthropomorphization should be investigated in different instructional domains and settings that involve learning about continuous movements and processes to prove whether they are in general a suitable method to enhance learning about processes with dynamic visualizations.

Further research should also investigate whether effective and less effective dynamic visualizations differ in their ability to activate the MNS, thereby potentially explaining inconsistent results on the effectiveness of dynamic visualizations (e.g., Höffler & Leutner, 2007; Tversky et al., 2002). The present study is one first step into this field of research and our results suggest that it is important to not only put further effort into designing better dynamic visualizations, but also in providing learners with suitable strategies to adequately process these visualizations.

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