Watching Non-Corresponding Gestures Helps Learners with High Visuospatial Ability to Learn about Movements with Dynamic Visualizations: An fNIRS Study

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Abstract

This study investigates whether making and observing (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 the animations of the to-be-learned movements twice. Depending on the condition, the second viewing was supplemented with either a self-gesturing instruction (Y/N) and/or a gesture video (corresponding/non-corresponding/no). Results showed that high-visuospatial-ability learners showed better learning outcomes with non-corresponding gestures, whereas those gestures were detrimental for low-visuospatial-ability learners. Furthermore, the activation of the inferior-parietal cortex (part of the hMNS) tended to predict better learning outcomes. Unexpectedly, making gestures did not influence learning, but cortical activation differed for learners who self-gestured depending on which gesture they observed. Results and implications are discussed.

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

Learning from Dynamic Visualizations

In recent years, dynamic visualizations such as animations and videos have become a popular instructional tool to visualize processes and phenomena that are dynamic in nature (e.g., cardiovascular system, lightning formation, fish movements). Obviously, dynamic visualizations are well-suited for this purpose given that they explicitly depict visuospatial information over time. Nevertheless, research thus far indicates that dynamic visualizations are often not superior to learning from static visualizations (e.g., Castro-Alonso et al., 2016; Mayer et al., 2005). It appears that dynamic visualizations are particularly effective for learning about movements when biological movement is involved (Hoffler & Leutner, 2007) like when learning to tie knots with the hands (Marcus et al., 2013) or learning to classify fish movements (Brucker et al., 2015). However, so far (1) there is only a handful of studies investigating the instructional potential of dynamic visualizations addressing biological movement and most of them focus on hand-manipulative tasks, and (2) it is yet unexplored to what extent learning about biological movements from dynamic visualizations can be enhanced by additional instructional support. These aspects provided the basis for the present study wherein we investigated the value of observing and making gestures for learning to classify fish movement patterns from dynamic visualizations.

Gestures and Learning

It is by now relatively well-established that making and observing gestures is beneficial for acquiring knowledge about different scientific topics and spatial problem solving (e.g., Chu & Kita, 2011; Cook & Goldin-Meadow, 2006). In learning about movements from dynamic visualizations, there is also increasing evidence that showing hands in manual tasks (e.g. origami folding, Marcus et al., 2013) or observing gestures in addition to the learning material improves learning outcomes (Brucker et al., 2015; De Koning & Tabbers, 2013). It is assumed that this is due to the activation of brain regions (i.e., the human mirror-neuron system [hMNS]; Fogassi & Ferrari, 2011; Rizzolatti & Craighero, 2004) involved in the observation, understanding and imitation of other persons' actions. This is in line with the current hypothesis that the stimulation and involvement of this hMNS might be beneficial for learning about complex continuous aspects with dynamic visualizations (Ayres et al., 2009; Van Gog et al., 2009).

Initial evidence for this comes from a study by Brucker et al. (2015) wherein low- and high-visuospatial-ability learners had to learn fish movement patterns from dynamic visualizations whilst observing additional gestures that did or did not correspond to the depicted movements. Results showed better learning outcomes and higher cortical activation in the inferior-frontal cortex (part of the hMNS) for low-visuospatial-ability learners after watching gestures that corresponded to the to-be-learned fish movements compared to watching non-corresponding gestures. High-visuospatial-ability learners achieved high learning outcomes with both gestures. Unexpectedly, low-visuospatial-ability learners who watched the non-corresponding gestures could also achieve high learning outcomes if they activated their inferior-parietal cortex (also part of the hMNS). These findings provide the first indication that the hMNS is also involved in representing non-human biological or even non-biological movements, if the observer is able to anthropomorphize these movements (cf. De Koning & Tabbers, 2011). So, drawing on the hMNS by showing learners gestures associated with the learning content seems an effective instructional strategy to improve learning about biological movements from dynamic visualizations.

Based on the notion that learner-generated gestures, as compared to just observing other's gestures, have a more direct and stronger influence on the degree to which the hMNS is activated (e.g., Montgomery, Isenberg, & Haxby, 2007), asking learners to make gestures related to the movements depicted in a dynamic visualization themselves may be a way to further enhance learning (cf. De Koning & Tabbers, 2011). Additional advantages of self-performed gestures relate to the manner (e.g., speed, amplitude) in which the gestures are made and the possibility to draw on one's personal experiences (with fish movement) in order to perform the gestures. By embodying the learning content in one's sensory and motor systems based on physical movements (i.e., gestures), the information is coded in a distinct, visuospatial representational format that enriches the way the information is represented, thereby creating a higher-quality mental representation (Paas & Sweller, 2012). Higher-quality mental representations are associated with better learning (Goldin-Meadow et al., 2001), yielding faster and more accurate performance on learning tests. It is important to note that these anticipated benefits only arise as long as the act of making gestures is not too demanding, complex or distracting (De Koning & Tabbers, 2013; Skulmowski et al., 2014). Together, by focusing on self-performed gestures whilst learning about biological movements from dynamic visualizations, we move into a promising but yet unexplored field of research (for an exception see De Koning & Tabbers, 2013).

Visuospatial Ability, Gestures, and Learning

As processing continuous changes requires visuospatial ability (cf. Hegarty, 1992), it is likely that learners' visuospatial ability will determine how much they benefit from dynamic visualizations and additional gestures (cf. Hegarty & Waller, 2005). According to previous research (e.g., Höffler, 2010) learners with higher visuospatial ability outperform learners with lower visuospatial ability during learning with visualizations, and visuospatial ability may moderate the effectiveness of learning with different instructions and 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; Höffler, 2010). For example, relating this to the Brucker et al. (2015) study, high-visuospatial-ability learners likely possess the skills and resources to see when gestures are in conflict with the depicted content and come up with an own strategy to elaborate on the relevant movements, whereas low-visuospatial-ability learners do not possess these skills and therefore are less able to deal with situations where gestures are in conflict with the dynamic visualizations resulting in lower learning outcomes. Thus, taking into account learners' visuospatial ability is relevant when studying the value of gestures in learning about movements from dynamic visualizations.

Present Study

This study addresses the question to what extent learning about biological movements from dynamic visualizations can be enhanced by adding information in the form of gestures. We implemented gesture-information in two ways: By *making gestures* of the learners themselves and by *observing gestures* displayed on a video. We investigated making gestures (by the learner) by contrasting (1) studying the dynamic visualizations whilst making gestures to (2) studying the visualizations without making gestures. Moreover, we examined observing gestures (that do or do not correspond to the depicted non-human biological movements) by contrasting studying the dynamic visualization whilst (1) observing corresponding versus (2) observing non-corresponding versus (3) not observing additional gestures. Furthermore, functional near-infrared spectroscopy (fNIRS), which is a non-intrusive neurophysiological method to gather data about cortical activation of humans, is used to investigate whether the hMNS is activated during viewing gestures and learning about biological movements from dynamic visualizations. We hypothesize that studying the dynamic visualization with additionally making gestures yields higher learning outcomes than studying without making gestures. Additionally, we hypothesize that studying the dynamic visualizations with additionally observing gestures yields higher learning outcomes than studying without observing gestures. In accordance with Brucker et al. (2015), this pattern is expected to vary as a function of level of gesture correspondence and learner's visuospatial ability: low-visuospatial-ability learners are expected to show higher learning outcomes only on corresponding gestures, whereas high-visuospatial-ability learners are expected to show improved learning outcomes for corresponding and non-corresponding gestures. Furthermore, we hypothesize that the hMNS is more strongly activated with self-performed gestures than with observed gestures, which in turn is more strongly activated than studying without gestures. Moreover, we hypothesize that higher hMNS activation is associated with higher learning outcomes. This is expected to be particularly true for low-visuospatial learners.

Methods

Participants and Design

One hundred and eighteen university students (M = 24.37 years, SD = 3.99; 84 females; 109 right handed) were recruited via an online system (http://www.orsee.org/) and compensated with 10 Euro. They had to learn to discriminate different fish according to their movements based on dynamic visualizations. There were four different to-be-learned movement patterns of fish. The participants saw each movement pattern twice: Firstly, they saw an animation of the specific movement pattern. Secondly, they saw the animation of the specific movement pattern again. But this time depending on the experimental condition, the animation could have been complemented with two additional sources: either a written instruction to self-gesture (making gestures) and/or a video of a person performing gestures with his hands and arms (observing gestures). Depending on this 2-by-3-between subjects design of the study with the two independent factors *making gesture* and *observing gesture* there were six conditions in total. *Making gesture* was varied in two variants: Participants either did or did not get the instruction "Please make your own gestures, that help you to better understand the movement." *Observing gesture* was varied in three variants: Participants either saw gestures that did correspond or that did not correspond (i.e., were unrelated) to the fish movement patterns or they saw no gesture at all (see Figure 1).

For the observing gestures conditions we used the gestures from Brucker et al. (2015). For the corresponding gestures, an expert regarding fish movements displayed with his hands and arms representations of the respective movements as clearly as possible, whereas for the non-corresponding gestures the (same) expert performed 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.

Participants saw the animation of the first fish movement for 30 s. Then a pause of 30 s (black screen) followed before they saw the animation of the first fish movement with its additions (depending on the experimental condition) for 30 s again. Then again a pause of 30 s (black screen) followed before the presentation of the next fish movement started in the same manner. The learners were instructed to relax in the pauses with the intention that the activations of the brain areas of interest were supposed to return to baseline level before the next visualization was displayed.

Materials

Participants were asked to learn to classify four different fish movement patterns. These fish movement patterns differ in terms of the parts of the body that generate propulsion (i.e., several fins or the body itself) and also in the manner of how these body parts move in the three-dimensional space (i.e. different paddle-like or wave-like movements). The four different movement patterns were: 1. oscillation of the pectoral fins; 2. undulation of the body; 3. undulation of the dorsal and anal fins; and 4. oscillation of the dorsal and anal fins (and undulation of the pectoral fins). During identifying these movement patterns it is very challenging that fish may deploy other movements in addition (e.g., to navigate) and these additional movements can easily be mistaken for movements used for propulsion in another movement pattern. We used the fish animations and gesture videos from Brucker et al. (2015). The movement cycles of the movement patterns were presented in loops in the animations (30 s per movement pattern, 25 fps, size: 480 x 360 pixels). The gestures were presented in the respective conditions in loops in the videos (30 s per movement pattern, 25 frames per s, size: 480 x 360 pixels). The presentation of all visualizations was system-controlled.

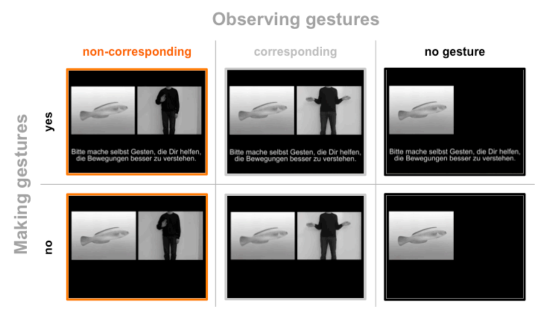

Figure 1: Six conditions in the 2-by-3-design of the study.

Measures

Learning Outcomes To assess learning outcomes, we administered a movement pattern classification test comprising 45 dynamic multiple-choice items. These items consisted of underwater videos of real fish performing one of the four to-be-learned movement patterns or a distractor movement pattern. Learners had to identify the body parts relevant for propulsion and their way of moving to choose for each item the kind of movement pattern that was depicted. Each item was visible for 7 s and immediately afterwards participants had 3 s time to choose the correct answer by pressing a corresponding button. Each item was awarded one point for the correct answer (0 to max. 45 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 To assess learners' visuospatial ability we used a short version of the paper folding test (PFT, Ekstrom et al., 1976; ten multiple-choice items; total processing time: three minutes). In this task, participants see five options from which they have to choose the correct answer. The stimuli are depictions of papers that are folded stepwise and then were punched in the folded state. The answer options depict unfolded papers with punches being either in the correct or incorrect positions. Each correct answer is worth one point (max. 10 points).

Cortical Activation During viewing the fish animation for the second time in the learning phase, cortical activation was assessed via fNIRS measurements with an ETG-4000 (Hitachi Medical Co.). We used a 2x22 channel array as probe set that was placed over fronto-temporo-parietal regions and was 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 for electrode placement (Jasper, 1958). The fNIRS system measures the change in the product of hemoglobin (Hb) concentration and effective optical path length in human brain tissue. The unit of Hb change is molar concentration (mM = mmol/l) multiplied by optical path length (mm). Local increases of Hb are indicators of cortical activity (Obrig & Villringer, 2003).

Procedure

Participants were tested individually. After reading a printed overview with information about the procedure of the study, they had to answer the demographics and the PFT. Then, the experimenter placed and adjusted the fNIRS probe set on the scalp of the participants. Subsequently, the computer-based learning materials were presented (learning phase). For each of the four to-be-learned movement patterns, learners were presented with the two presentations of the fish animations (1. fish animation and 2. fish animation plus additional gesture video and/or self-gesturing instruction depending on the experimental condition). Following the learning phase (8 min) learners performed a filler task (about 8 min), in which they answered some questions on object positions of depicted objects. Subsequently, learners completed the movement classification test (15 min). Participants were instructed to put both their forefingers and both their middle fingers on predefined keys as well as one of their thumbs on the space bar to answer the test items. The predefined keys were labeled on the screen with static screenshots from the learning animations of the four movement patterns and the spacebar was labeled with a grey bar indicating movements that were not part of the learning phase (i.e. distractor items). In total, one experimental session lasted approximately 50 minutes.

Results

Learning Outcomes

To analyze learning outcomes, we conducted an ANCOVA (univariate analysis of covariance) with the factors *making gesture, observing gesture,* and the continuous factor *learners' visuospatial ability* as a covariate. We inserted all interaction terms in the analysis to investigate the possible interactions. For learning outcomes, results showed no main effect of making gestures ($F < 1$, ns), no main effect of observing gestures ($F(2, 106) = 1.65$, $MSE = 119.63$, $p = .20$, $\eta^2_p = .03$, ns), but there was a significant main effect for learners' visuospatial ability ($F(1, 106) = 11.58$, $MSE = 119.63$, $p = .001$, $\eta^2_p = .10$). This effect has to be interpreted in terms of the significant interaction between observing gestures and learners' visuospatial ability on learning outcomes ($F(2, 106) = 7.93$, $MSE = 119.63$, $p = .001$, $\eta^2_p = .13$; see means and standard errors in Figure 2). There were no other significant interactions or three-way-interactions (all ps > .35, ns). The significant interaction between observing gestures and learners' visuospatial ability on learning outcomes showed that for participants with high visuospatial ability (defined as one standard deviation above the sample mean) the non-corresponding gesture led to better learning outcomes than the corresponding gesture ($p = .001$) and no gesture ($p = .02$). For participants with low visuospatial ability (defined as one standard deviation below the sample mean) non-corresponding gestures were worse for learning than no gesture ($p < .01$), whereas there was no significant difference between the corresponding gesture condition and the no gesture condition ($p = .23$, ns). Thus, the non-corresponding gestures are beneficial for high-, but detrimental for low-visuospatial-ability learners.

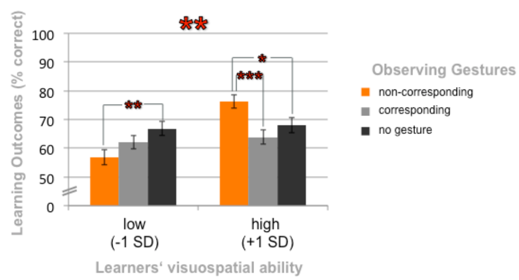

Figure 2. Interaction between learners' visuospatial ability and observing gestures on learning outcomes.

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 (cf. Rizzolatti & Craighero, 2004). The two ROIs were the left inferior-frontal cortex (IFC) and the left inferior-parietal cortex (IPC, cf. Figure 3). Cortical activation in these areas was analyzed with two ANCOVAs with the factors *making gestures, observing gestures,* and *learners' visuospatial ability* as a covariate. We had to exclude five participants from these analyses because of poor data quality resulting in a total number of 113 participants in these analyses. Even though making gestures did not influence results on learning outcomes, analyses on cortical activation showed tendencies for an interaction between making gestures and observing gestures for both IFC activation ($F(2, 100) = 2.94$, $MSE = .001$, $p = .06$, $\eta^2_p = .06$) and IPC activation ($F(2, 100) = 2.42$, $MSE = .001$, $p = .06$, $\eta^2_p = .05$). There were no other significant main effects or interactions in these analyses (all ps > .104, ns). Pairwise comparisons revealed that participants observing corresponding gestures showed higher IFC activation if they self-gestured than when they did not self-gesture ($p = .005$). However, participants observing non-corresponding gestures showed higher IPC activation if they self-gestured than when they did not self-gesture ($p = .02$). This might be an indicator that during watching corresponding gestures the

IFC is more important, whereas during processing non-corresponding gestures the IPC becomes more important – at least when the participants were instructed to self-gesture.

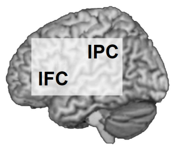

Figure 3. Spatial arrangement of the left probe set.

Effects of Cortical Activation on Learning

To address the question whether higher hMNS activation is directly associated with better learning outcomes, we conducted two ANCOVAs with the factors *making gestures*, *observing gestures, learners' visuospatial ability* and cortical activation in terms of *IFC activation* or *IPC activation*, respectively. There was a tendency that higher IFC activation lead to higher learning outcomes ($F(1, 88) = 3.22$, $MSE = 124.85$, $p = .08$, $\eta^2_p = .04$). This analysis on IFC activation did also show the main effect for visuospatial ability ($F(1, 88) = 7.58$, $MSE = 124.85$, $p < .01$, $\eta^2_p = .08$) as well as the interaction between observing gesture and visuospatial ability ($F(2, 88) = 3.93$, $MSE = 124.85$, $p = .02$, $\eta^2_p = .08$; both effects reported for learning outcomes, see Figure 2). For IFC activation there were no other significant main effects or interactions (all *p*s > .27, ns). The analysis on IPC activation did also show the main effect for visuospatial ability ($F(1, 88) = 7.18$, $MSE = 128.56$, $p < .01$, $\eta^2_p = .08$) and the interaction between observing gesture and visuospatial ability ($F(2, 88) = 5.18$, $MSE = 128.56$, $p < .01$, $\eta^2_p = .11$; both effects reported for learning outcomes, see Figure 2). For IPC activation there were no other significant main effects or interactions (all *p*s > .189, ns).

Discussion

This study investigated whether making and observing additional gestures improves learning about biological movements from dynamic visualizations and to what extent this is related with the cortical activation in areas associated with the hMNS. Regarding learning outcomes, our results indicate that the observation of gestures has different effects for high- and low-visuospatial-ability learners, particularly when dealing with non-corresponding gestures. For high-visuospatial-ability learners, non-corresponding gestures improved learning (even beyond corresponding gestures), whereas for low-visuospatial-ability learners the observation of non-corresponding gestures had detrimental effects on learning. These findings are largely in line with those reported by Brucker et al. (2015) and indicate that particularly when high-visuospatial-ability learners are challenged by a desirable difficulty (cf. Schüler, 2017), in this case by creating a conflict between the visualized fish movements and the (mismatching) gestures, they are stimulated to put more effort in reducing the conflict and come up with a strategy to more elaborately process the relevant movements. This in turn increases the chance that they properly understand the depicted movement. In contrast, low-visuospatial-ability learners presumably are insufficiently equipped for managing such a situation of conflicting information (e.g., they do not have the resources to identify the mismatch or do not know how to cope with that), and are not able to accurately process the movements and to avoid reduced performance.

In this study, IFC activation tended to predict better learning outcomes. However, compared to the Brucker et al. (2015) study, we did not find the result pattern that IPC activation compensates for missing support of visuospatial ability or non-conflicting gestures. This might be explained by the fact that in the present study participants who neither have visuospatial ability nor non-conflicting gestures at their disposal (i.e. the group of low-visuospatial-ability learners who saw non-corresponding gestures) still could focus on the fish animation. This was possible because in this study the gestures were presented at the same time as the fish, whereas in our prior study the gestures were presented separated in time from the fish animations. However, further research should investigate direct comparisons of sequential and simultaneous presentations of additional gestures.

Another interesting result of this study is that, in contrast to our hypothesis, self-performed gestures did not improve learning outcomes. In line with this, several recent attempts to augment learning about non-human movement (e.g., lightning formation, grammar rules) by instructing learners to make gestures while studying an animation also failed to improve learning performance (e.g. De Koning & Tabbers, 2013; Post et al., 2013). Collectively, the conclusion from this and other studies is that independent from timing of gestures (during or after learning from dynamic visualizations) and instructional approach (instruct specific ways to perform gestures or let learners decide how to perform gestures) making gestures does not seem to benefit learning from dynamic visualizations involving non-human movement. Importantly, however, making gestures did activate the hMNS. Participants who were instructed to self-gesture activated different parts of the hMNS depending on which gesture they simultaneously observed: with the corresponding gestures there was higher IFC activation, whereas with the non-corresponding gestures there was higher IPC activation. This can be brought in line with our previous findings (Brucker et al., 2015), in which we also found evidence that the IFC plays a role during watching corresponding gestures, whereas the IPC comes into the picture when (conflicting) non-corresponding gestures have to be processed. The IPC is associated with processes of motion analysis and motor imagery, which may both be helpful in the context of identifying the mismatch between the to-be-learned movements and the non-corresponding gestures. However, future research is needed to explore these processes in more detail. Future research should also address one limitation of this study – namely the lack of insight into learners' strategies – by replicating it with think-aloud protocols so that it is possible to discover the strategies learners use when observing and making (non-corresponding) gestures in learning from dynamic visualizations. Furthermore, it is important to further identify potential neural correlates of (gesture-supported) learning with dynamic visualizations and to further unravel the relations between activation in different parts of the brain and learning outcomes. The present study provides a starting point from which future research endeavors within this emerging field of research can be explored with the goal to incorporate (observing and making) gestures in a way that learning about non-human movements from dynamic visualizations is enhanced. In conclusion, this study shows that observing additional gestures is helpful for learning about movements, but learners need different types of gestures depending on their amount of visuospatial ability. Thus, different types of gestures should be applied: High-visuospatial-ability learners should be challenged with non-corresponding gestures, whereas low-visuospatial-ability learners might be supported with corresponding gestures.

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