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Authors
Imhof, Birgit
Scheiter, Katharina
Edelmann, Jorg
et al.

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Is enriching static-simultaneous visualizations with motion-indicating arrows helpful for learning about locomotion patterns?

Birgit Imhof (b.imhof@iwm-kmrc.de)

Katharina Scheiter (k.scheiter@iwm-kmrc.de)

Jörg Edelmann (edelmann@gris.uni-tuebingen.de)

Julian von Ulardt (julian.von-ulardt@student.uni-tuebingen.de)

Peter Gerjets (p.gerjets@iwm-kmrc.de)

Knowledge Media Research Center, Konrad-Adenauer-Strasse 40, 72072 Tuebingen, Germany

Abstract

In the current study, multiple static-simultaneous visualizations were combined with motion-indicating arrows and were compared either to multiple static-simultaneous visualizations without arrows, which proved to be effective in former studies concerning static visualizations, or to a single static visualization enriched with motion-indicating arrows. Seventy-one students were randomly assigned to the three conditions. Learning outcomes were measured by pictorial tests at three difficulty levels. Contrary to our expectations the results showed that the combined condition (multiple static-simultaneous visualizations with arrows) was worse than both other conditions on the critical intermediate tests. Therefore, it seems that multiple static-simultaneous visualizations without any further enriching components and single static visualizations with motion-indicators have their own facilitating effects on fostering mental animation. These effects are possibly caused either by supporting comparisons among simultaneously presented multiple pictures or by showing the dynamic information (more) explicitly and thereby stimulating and guiding mental imagery of the movements, respectively.

Keywords: learning; multiple static-simultaneous visualizations; enriching static visualizations; motion-indicating arrows; spatial ability.

Learning about Locomotion Patterns

Learning about biological locomotion patterns is a task that addresses a highly dynamic process rendering it essential to acquire a correct understanding of the continuity of different movements. Recognizing locomotion patterns is essential for human beings, since a prolific interaction with the environment relies on fast, exact interpretations of objects and their movements (Chatterjee, Freyd, & Shiffrar, 1996).

The use of dynamic visualizations seems to be an appropriate strategy to convey knowledge about locomotion patterns (i.e., dynamic processes; e.g., Höffler & Leutner, 2007; Tversky, Bauer-Morrison, & Bétrancourt, 2002). The option to explicitly depict changes over time and space in dynamic visualizations offers learners the possibility to directly observe the continuity of these changes (Lowe, 2003). Thus, there is no need for learners to infer changes,

as it would be the case with static pictures (cf. mental animation; Hegarty, 1992). On the other hand, dynamic visualizations may impose high perceptual and cognitive demands onto learners. First, these demands are caused by the transience of dynamic visualizations, where learners have to keep previously shown information in memory to integrate it with later information (e.g., Hegarty, 2004; Lowe, 1999). Moreover, there are often several things going on at the same time in dynamic visualizations and therefore learners have to divide their attention among multiple locations in the display. This is particularly a problem, if the relevant aspects are not the most salient ones, because then learners almost automatically may be distracted by other salient, but irrelevant dynamic aspects (Lowe, 2003).

For these reasons, dynamic visualizations may sometimes yield equal performance compared to static visualizations or under specific circumstances static visualizations may even prove to be superior (e.g., Mayer et al., 2005). One may argue that static visualizations can be helpful for understanding continuous changes, despite the fact that they do not show these changes explicitly, if they are designed in a way that facilitates mental animation (e.g., Paas, Van Gerven, & Wouters, 2007). There are, at least, two different possible solutions to facilitate mental animation in static visualizations. Firstly, depicting multiple states by means of multiple static pictures seems to be an adequate strategy to present information in static visualizations in a way that facilitates mental animation, because with multiple pictures different positions of objects relevant for mentally reconstructing the movements can be shown explicitly (e.g., Imhof et al., 2010). Information on these different positions is likely to be required to infer the continuity by means of interpolation between the depicted states of relevant objects and their positions. Secondly, another strategy to facilitate mental animation in static visualizations is to enrich them with motion-indicating arrows (e.g., Münzer, Seufert, & Brünken, 2009). This can be helpful to indicate the continuous changes in static visualizations. Instead of interpolating between different states, learners are encouraged to extract and process the information of the

arrows and to build a mental model concerning the indicated dynamic processes.

Multiple Static(-Simultaneous) Visualizations

When using multiple static pictures one has to decide upon their presentation format. One important issue is that the static visualizations can vary with respect to the pictures' sequentiality (cf. Lowe, Schnotz, & Rasch, 2010): They may be presented either (a) sequentially, that is, one after another at the same position on the screen so that earlier pictures are replaced by later ones, or (b) simultaneously, that is, all pictures next to each other together on one page. The latter presentation format is the typical way of presenting visualizations in static media such as textbooks.

In a static-simultaneous presentation the depicted information remains visible on the screen. Therefore, this presentation format allows for an interpolation between states that is based on an external representation, where comparisons among discrete steps are enabled. These comparisons can be used to infer the changes between the different positions of relevant objects, thereby potentially facilitating mental animation. Moreover, in a static-simultaneous presentation learners can regulate the pacing of their cognitive processing by deciding when to move their attention from one picture to another. However, no spatial alignment of relevant objects is given in static-simultaneous visualizations, which would be the case in static-sequential visualizations because the relevant elements are presented at almost identical spatial positions.

Former research showed that the sequentiality of multiple static pictures influences how well mental animation is supported by the respective visualizations. Multiple static-simultaneous visualizations were shown to be as good for learning a task that requires the correct understanding of dynamic processes (i.e., locomotion pattern classification) as dynamic ones, whereas learners with multiple static-sequential visualizations performed worse than those studying dynamic visualizations (e.g., Imhof et al., 2010). Moreover, the same results were shown in a mechanical domain by Boucheix and Schneider (2009). Both findings can be explained by the aforementioned benefits of multiple static-simultaneous visualizations for supporting mental animation. However, for tasks that do not require the correct understanding of the dynamic processes (e.g., sorting tasks, verbal comprehension tests) static-sequential visualizations might be likely sufficient or even superior, as shown by Lowe et al. (2010) or Kim et al. (2007). Nevertheless, our previous research findings show that presenting multiple static pictures simultaneously is an adequate strategy to foster the task of classifying visual test stimuli in the domain of learning about locomotion patterns.

Motion-Indicating Arrows

As aforementioned, a second compelling candidate for conveying changes over time in static visualizations consists in the provision of arrows (Heiser & Tversky, 2006). Arrows add extra information to visualizations (Tversky et al., 2008) and are often used to guide learners' attention (i.e., attention cueing; e.g., DeKoning et al., 2009). However, arrows may not only function as pointers towards specific elements in visualizations, but they can also be used to convey information concerning motion of relevant objects (translations; e.g., Bétrancourt, 2005). Tversky et al. (2008) state that to indicate motions of objects an arrow is the best alternative. This strategy of depicting arrows to indicate the movements of the relevant objects can be applied to static visualizations, thereby enriching static visualizations with additional information (Münzer et al., 2009). Motion-indicating arrows can stimulate the mental animation process and also serve as guidance "through" the motion that has to be processed. Potentially, once arrows are provided, even single static pictures may be suited to convey information concerning the motion of objects. In the study of Münzer et al. (2009) enriched multiple static visualizations outperformed static visualizations without arrows as motion-indicators (particularly for learners with high spatial abilities) in tests on process knowledge in a biological domain. In line with this finding, we investigated whether mental animation of locomotion patterns can be supported by presenting motion-indicating arrows. Furthermore, we directly investigated whether a combination of multiple static-simultaneous visualizations with motion-indicating arrows is even more effective than enriching a single static visualization.

Beyond these design issues, recent research on learning from visualizations has also shown that learner prerequisites can affect the effectiveness of visualizations during learning about locomotion patterns. In particular, learners' spatial ability may play a role, because the understanding of biological locomotion patterns requires the processing of spatial information and the processing of this information requires spatial abilities.

The Role of Spatial Ability

Hegarty (1992) proposed that learners' spatial ability plays a role for the process of mental animation. Her empirical evidence showed that learners with stronger spatial abilities were better able to infer the motion of a pulley system based on a single static visualization than learners with weaker spatial abilities. These findings are confirmed by a recent meta-analysis revealing that learners with higher spatial abilities outperform learners with lower spatial abilities during learning with visualizations (Höffler, 2010). Accordingly, for the current study high spatial ability learners were expected to outperform low spatial ability learners in all three conditions.

Moreover, there is some evidence that spatial abilities may moderate the effectiveness of learning with different visualization formats. For instance, Hays (1996) showed in a physics domain that low spatial ability learners particularly benefited from learning with dynamic visualizations compared to static ones or no visualizations suggesting that these learners have fewer abilities to mentally animate the dynamics based on static pictures.

This also implies that learners with higher spatial ability may compensate for "poor" instructions (i.e., visualizations that do not support mental animation well), whereas learners with lower spatial ability suffer from such instructions (cf. ability-as-compensator hypothesis, Mayer & Sims, 1994; see also Boucheix & Schneider, 2009; Höffler, 2010). Accordingly, we assumed that benefits in favour of the condition that combined multiple static-simultaneous visualizations with arrows would be more pronounced for learners with lower rather than higher spatial abilities during learning how to recognize locomotion patterns.

Hypotheses

We assumed that the combination of multiple (static-simultaneous) visualizations with (motion-indicating) arrows would lead to superior learning outcomes than both multiple (static-simultaneous) visualizations without (motion-indicating) arrows, as well as single (static) visualizations with (motion-indicating) arrows. Moreover, we assumed that higher spatial ability would be associated with better learning outcomes than lower spatial ability. Furthermore, we assumed that benefits in favour of the combined condition would be more pronounced for learners with lower rather than higher spatial abilities during learning how to recognize locomotion patterns, whereas we did not hypothesize such a differentiation for the two other conditions (multiple visualizations without arrows and single visualization with arrows).

Method

Participants and Design. We randomly assigned 71 university students (average age: 23.79 years, $SD = 4.59$; 46 female) from a German university to one of three visualization conditions: multiple visualizations without arrows vs. multiple visualizations with arrows vs. single visualization with arrows. The students participated for either payment (10 Euro) or course credit.

Materials. Participants were asked to learn how to classify fish according to their locomotion patterns based on visualizations. These locomotion patterns differed in terms of the used body parts that generate propulsion (i.e., the body itself or several fins) and also in the manner of how these body parts are moving (i.e., wave-like or paddle-like). The following four locomotion patterns were used in this study: 1. *subcarangiform*: undulation of the body as a whole; 2. *balisitiform*: undulation of the dorsal and anal fins; 3. *tetraodontiform*: oscillation of the dorsal and the anal fins (and possibly undulation of the pectoral fins); and 4. *labriform*: oscillation of the pectoral fins. One of the major challenges in identifying these locomotion patterns is that fish may deploy a variety of other movements in addition, for instance, for navigation. These navigational movements used by a fish displaying a specific propulsion locomotion pattern can easily be confused with movements used for propulsion in another locomotion pattern.

We developed highly realistic 3D-models of fish performing the four to-be-learned locomotion patterns based on which animations were rendered that were standardized in terms of the spatial orientation, the background, and the position of the fish and that included no miscellaneous movements. A domain expert extracted the static pictures used in this study from these animations to ensure that the key states in the movement cycles are presented.

We varied the *presentation format* of the visualizations as independent variable. In the multiple visualizations without arrows condition nine static key pictures depicting the whole movement cycles were presented in parallel in two rows (cf. Imhof et al., 2010; see Figure 1 for an example). They were arranged corresponding to the two important phases of the locomotion patterns. To facilitate the transition from the first to the second row, the fifth picture was depicted twice, once as the last picture of the upper row and once as the first picture of the lower row. The pictures' sizes in the multiple visualization conditions (with and without arrows) were 240 x 180 pixels. This size ensured that all pictures fitted on the screen at once and thus, there was no need to scroll a page.
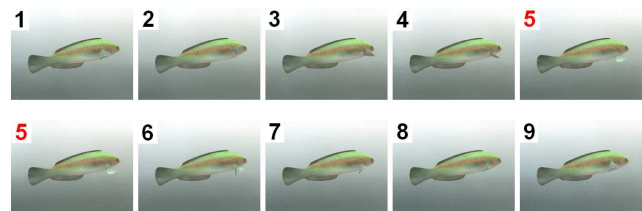

Figure 1: Spatial arrangement of the multiple static-simultaneous pictures (positions indicated by numbers).

In the single visualization with arrow condition only the first static key picture of each movement cycle was presented and augmented with motion-indicating arrows (see Figure 2). Undulating movements were indicated by wavelike arrows above/below the respective body parts. Oscillating movements were indicated by bent arrows, whereby the bending corresponded to the trajectory of the moving elements. The pictures' size in the single static visualization condition was 480 x 360 pixels.
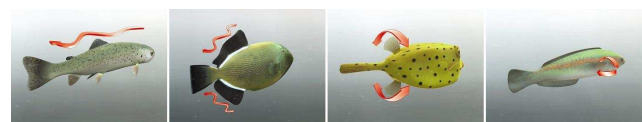

Figure 2: Single static visualizations of the four to-be-learned locomotion patterns with motion-indicating arrows (from left: *subcarangi-; balisti-; tetraodonti-; labriform*).

In the combined condition (multiple visualizations with arrows), we added the motion-indicating arrows to the first picture (see Figure 3 for an example). The arrows were depicted only on the first picture of the multiple

visualizations to stimulate mental animation without overloading the visual display.

During learning the participants saw visualizations for each of the four to-be-learned locomotion patterns in a predefined order within a multimedia learning environment. The presentation was system-controlled and accompanied by narration. The narration explained the locomotion pattern in terms of conceptual characteristics: body parts involved, kind of movements executed (undulation versus oscillation), parameters of the movements (e.g., amplitude), maximum velocity, and typical fish using this locomotion pattern. It is important to note that the narration conveyed many aspects that were not visible in the visualizations (e.g., maximum velocity) and that would not have been sufficient to help classify a fish according to its locomotion alone.
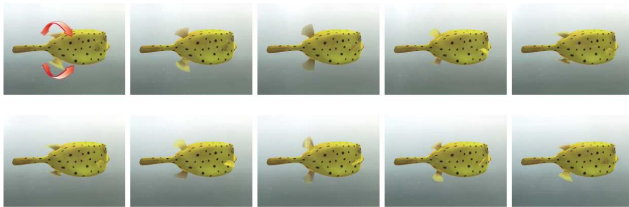

Figure 3: Multiple static-simultaneous visualization with motion-indicating arrow on the first picture.

Measures. Learners' spatial abilities were assessed with two different tests, namely the mental rotation test (MRT, Vandenberg & Kuse, 1978), and a shortened version of the paper folding test (PFT, Ekstrom et al., 1976). Both measures were used in the analyses as continuous factors.

Learning outcomes were assessed with a locomotion pattern recognition test with 28 pictorial multiple-choice items consisting in underwater videos of real fish performing the locomotion patterns that had to be correctly recognized. The dynamic test items differed from the static learning materials with respect to fish species, color, and body shape. Therefore, learners could not rely on these characteristics to give the correct answer. Moreover, because the test items consisted in videos of real fish, they also contained irrelevant information and sometimes miscellaneous movements of the fish that were not relevant for propulsion. To choose for each item the kind of locomotion pattern that was depicted, learners had to identify the body parts relevant for propulsion and their way of moving. Possible answers were the correct terms of the four locomotion patterns and the additional answer "I don't know" (see Figure 4 for an example). Each item was awarded one point for the correct answer (max. 28 points). The recognition test items were categorized by two independent domain experts into items with low (8 items), intermediate (11 items), and high task difficulty (9 items). Their decisions were based on the visibility of movements relevant for propulsion as well as on the absence or presence of miscellaneous movements that could have been mistaken as being relevant for propulsion (cf. Imhof et al., 2010).

Figure 4: Screenshot of a recognition test example item (correct answer: *balistiform*).

Procedure. Though participants worked on all parts of the study individually, they were tested in groups of two to seven persons. They were separated by partition walls. After completing the MRT, PFT, and a demographic questionnaire (all paper-based), participants read an introduction, which was followed by the computer-based learning phase, in which the participants heard the narration via headphones. Finally, learners worked on the computer-based pictorial recognition test. One experimental session lasted about one hour.

Results

Performance in the three recognition subtests was analyzed by a MANCOVA with presentation format (multiple visualizations without arrows versus multiple visualizations with arrows versus single visualization with arrows), the MRT, and the PFT as independent variables (for adjusted means and standard errors see Table 1). Because of space limitations, statistical values are only reported for significant results.

Table 1: Adjusted means (and standard errors) for recognition performance (in percent correct) as a function of presentation format and task difficulty.

Task Diffi- culty	Presentation Format		
	multiple visualizations without arrows (n = 24)	multiple visualizations with arrows (n = 24)	single visualization with arrows (n = 23)
low	85.78 (4.02)	76.87 (3.94)	84.98 (4.06)
inter- mediate	76.98 (4.31)	60.86 (4.23)	81.39 (4.35)
high	68.38 (4.58)	59.40 (4.48)	67.09 (4.62)

There was a marginal overall effect for presentation format (Wilks $\lambda = .82$; $p < .10$) and for the PFT (Wilks $\lambda = .96$; $p < .10$). Subsequent ANCOVAs revealed that there was a main effect of presentation format only for items with intermediate task difficulty ($F(2,62) = 6.26$, $p < .01$, $\eta^2 = .17$), which also were the items that proved to be the most sensitive ones in former studies (Imhof et al., 2010).

Contrary to our expectations, Bonferroni tests showed that learners in the combined condition (multiple visualizations with arrows) performed worse than both the multiple visualizations without arrows condition ($p < .05$) and the single visualizations with arrows condition ($p < .01$). There were no differences between the latter two conditions.

Subsequent ANCOVAs revealed further that for recognition tasks with low and intermediate task difficulty higher performance in the PFT was associated with better recognition (low difficulty: $F(1,62) = 6.27$, $p < .05$, $\eta^2 = .09$; intermediate difficulty: $F(1,62) = 4.00$, $p < .05$, $\eta^2 = .06$).

Discussion

Contrary to our hypothesis that the combination of multiple static-simultaneous visualizations with motion-indicating arrows (combined condition) would lead to superior learning outcomes than both other conditions we found that both the multiple visualizations without arrows condition as well as the single visualization with arrows condition were better for learning about locomotion patterns than the combined condition – as evident in the performance on tasks with intermediate difficulty. Therefore, it seems that the multiple visualizations without arrows as well as the single visualization with arrows have their own facilitating effects with respect to fostering mental animation.

In particular, the positive effects of the multiple visualizations without any further enriching components and the single visualizations with motion-indicating arrows for tasks with intermediate difficulty might be caused either by supporting comparisons among simultaneously presented multiple pictures or by showing the dynamic information (more) explicitly and thereby stimulating and guiding mental imagery of the movements, respectively.

However, when combining these two approaches to foster mental animation during learning about locomotion patterns, interferences between competing processes seem to occur, which may explain why learners in the combined condition showed worse performance. Probably, learners were somehow overloaded when they were stimulated by the instructional materials to compare different key states in multiple visualizations and to mentally imagine the movements on the basis of an arrow at the same time. Eye-tracking research on mental imagery shows that learners tend to follow the imagined trajectories with their eyes (e.g., Johansson, Holsanova, & Holmqvist, 2006). But in doing so, a learner can not switch his/her attention forth and back at the same time on the relevant pictures for visual comparison processes. Following Beck (1991) instructional designers have to be careful when composing different cueing strategies, because such combinations will not always aid learning by complementing each other, even if both strategies proved to be facilitating in isolation. The results of our study suggest that this holds not only true when combining different cueing strategies, but also when combining cueing strategies with other instructional approaches. Even though the arrows and the set of multiple visualizations in principle convey the same information,

they do it differently and learners therefore might have had problems to integrate these two elements of the visual materials. An alternative explanation might be that the learners did not notice that the arrows depicted the same movements as the set of multiple visualizations even though they were told about this fact in the instruction beforehand. Interestingly, single visualizations with arrows – that is the most parsimonious representation format – achieved the same performance level as multiple static-simultaneous visualizations. Accordingly, learners – when stimulated to mentally animate an object by a motion-indicating arrow – seem to be well able to achieve an understanding of the dynamics even based on sparse information only.

However, this result pattern was only present for the tasks with intermediate difficulty. For items with low task difficulty a ceiling effect might have occurred. These items seemed to be so clearly identifiable that learners from all three experimental conditions achieved rather good results. On the contrary, for items with high task difficulty the locomotion patterns were not clearly identifiable based on the perceptual input alone according to the experts' opinions. Rather conceptual knowledge that might have been acquired from the narration, which were identical in all experimental conditions, had to be used to answer these items. Thus, these items might not be sufficiently responsive for manipulations of the perceptual input.

Our hypothesis that learners' spatial ability would be positively correlated with task performance was at least partially confirmed, that is, for spatial abilities as measured by the PFT, but not the MRT. This finding is well in line with the recent meta-analysis by Höffler (2010). However, the low spatial ability learners might have relied strongly on the narration (particularly if they are challenged by the visual inputs) to understand which elements are relevant for propulsion. Thus, they had to infer from the visual input only how these elements move. This might have helped them to perform relatively well in all three conditions. Accordingly, contrary to our expectations and former results, we were not able to find the moderating effect of learners' spatial abilities concerning the effectiveness of different presentation formats of visualizations. Therefore, the assumed ability-as-compensator hypothesis that higher spatial ability learners may compensate for "poor" instructions (i.e., visualizations that do not support mental animation well), whereas lower spatial ability learners suffer from such instructions, could not be confirmed. It is worth noting that the results suggest that the visualizations that support mental animation well seem to be, contrary to our expectations, the multiple visualizations without arrows and the single visualization with arrows. Regarding the results, the combined condition is the "poor" instruction in our data. Seen from this angle, the combined condition does not benefit from especially high spatial abilities as in the study of Münzer et al. (2009). However, as the ability-as-compensator hypothesis has been shown in former research exclusively for dynamic visualizations, it might not be too surprising that we did not find evidence in this direction.

To conclude, this study demonstrates that there are several effective strategies, based on mental animation facilitation, to stimulate perceptual processing of static visualizations to support knowledge acquisition about biological locomotion patterns. However, using more than one supporting strategy might stimulate competing processes, resulting in interferences that hinder learning. Therefore, in further research one should put effort into research on how to optimize the single strategies, instead of combining these two approaches.

Acknowledgments

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