The Role of Dynamic Visualizations and Spatial Layout of Static Visualizations for Learning How to Classify Locomotion Patterns

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Abstract

In two studies the effectiveness of dynamic and multiple static visualizations was investigated for a highly perceptual learning task, namely locomotion pattern classification. In Study 1a, seventy-five students viewed either dynamic, static-sequential, or static-simultaneous visualizations. For tasks with intermediate difficulty dynamic visualizations led to better recognition of the locomotion patterns than static-sequential visualizations, but not than static-simultaneous visualizations. To test whether the presentation of the static-simultaneous visualizations in rows or their permanent visibility was accountable for this effect, three additional static-simultaneous conditions were investigated in Study 1b. Seventy-five students viewed the static-simultaneous visualizations either presented in columns, in matrices, or in circles. The dynamic condition outperformed all three additionally investigated static-simultaneous conditions in the intermediate tasks. Accordingly, for learning how to classify locomotion patterns dynamic visualizations are better suited than most static presentation formats. Nevertheless, presenting static-simultaneous visualizations appropriately can achieve equal results at least for tasks with intermediate difficulty.

Keywords: learning; dynamic visualizations; multiple static visualizations; spatial ability

Learning with Visualizations

Dynamic visualizations have not always been found to lead to better learning than static visualizations (Tversky, Bauer-Morrison, & Bétrancourt, 2002). Bétrancourt and Tversky (2000) have suggested that dynamic visualizations should be superior only for specific tasks. In particular, they will aid learning if understanding the content explicitly requires understanding of its dynamic aspects like trajectory or continuity of changes. These dynamic aspects can be conveyed directly through a dynamic visualization. Thus, in many studies in which dynamic visualizations failed to be beneficial, a direct depiction of the contents' dynamic aspects may not have been necessary (e.g., Byrne, Catrambone, & Stasko, 1999). On the other hand, tasks that require a profound understanding of continuous changes often benefit from dynamic visualizations (e.g., hand manipulation tasks, Ayres et al., 2009; Wong et al., 2009).

Similarly, the current study focuses on a task that explicitly requires identifying the continuity of the depicted dynamics and involves a strong perceptual component, namely recognizing biological locomotion patterns of fish as a basis of species classification. To accomplish this task, it is important that learners correctly perceive the underlying kinematics, for instance, to decide whether a fin moves in a wave-like or a paddle-like manner. The continuity of these dynamics can be shown explicitly only in dynamic visualizations. However, one can argue that multiple static visualizations may also foster the understanding of continuity, but that this is likely to depend on how they are presented. In particular, to foster the understanding of continuity static pictures have to be presented in a way that they facilitate mental animation (e.g., Paas, Van Gerven, & Wouters, 2007). Mental animation is the process of inferring movements from static pictures based on knowledge about relevant components and their causal relations to other components (Hegarty, 1992). We assume that both, temporal as well as spatial aspects of presenting static pictures affect how well they support mental animation.

Temporal Aspects of Presenting Static Pictures

The main difference concerning temporal aspects of presenting multiple static pictures is their sequentiality. They can be depicted either sequentially or simultaneously. In a sequential presentation one picture is shown after another at the same position, whereby later pictures replace former ones. In a simultaneous presentation all pictures are shown next to each other on a single screen. The temporal alignment of visual elements is easier in a sequential presentation because elements that are identical across the pictures are depicted at identical spatial positions (unless they change their position over time). However, to make comparisons between relevant objects the information of earlier pictures has to be memorized until later pictures are shown (Paas et al., 2007). Hence, integrating information across the pictures may be challenging for learners. In contrast, in a simultaneous presentation the depicted information remains visible on the screen and therefore comparisons among discrete steps are enabled. Moreover, in static-simultaneous visualizations learners can regulate the pacing of their cognitive processing by deciding when to look at a picture and for how long. This all suggests that a simultaneous presentation of static pictures may be better suited to foster mental animation than a sequential one.

This assumption was confirmed by Boucheix and Schneider (2009), who found that static-simultaneous visualizations were as good for understanding a mechanical system as dynamic ones and that they outperformed static-sequential ones. This was especially true for learners with low spatial ability (but see Kim et al., 2007). For the locomotion pattern classification task used in the current study, we found a very similar result pattern, namely that dynamic visualizations outperformed static-sequential ones, whereas static-simultaneous visualizations reached the same performance as dynamic ones (Imhof, Scheiter, Gerjets, 2009). These findings suggest that dynamic visualizations may not be the only solution to convey knowledge about dynamic changes. The first part of the current study (Study 1a) focused on replicating the findings of Imhof et al. (2009) with more standardized visualizations and a broader range of classification tasks at different levels of difficulty.

Spatial Aspects of Presenting Static Pictures

When using static-simultaneous visualizations the question arises of how to arrange the static pictures on the screen to facilitate mental animation. In the study by Imhof et al. (2009) as well as in Study 1a the static pictures were represented in two rows of five pictures each. A row representation requires comparisons between different pictures to be made from left to right or vice versa. This should be advantageous for several reasons: Firstly, it corresponds to the reading order for texts (in Western cultures) and is also common for other static-simultaneous visualizations (e.g., comics). Secondly, eye tracking research has shown that irrespective of the depicted stimulus horizontal eye movements are more likely to occur than vertical ones (Tatler & Vincent, 2008). Finally, arranging multiple visualizations of an object that is moving from left to right in a row corresponds to the moving direction of this object. Taken together, a row presentation should facilitate mental animation, because it better corresponds to the nature of the depicted movement as well as to our typical viewing behavior. This may be why it is also the common presentation format for static-simultaneous visualizations used in former studies (Boucheix & Schneider, 2009; Imhof et al., 2009; Kim et al., 2007). However, it is unclear whether the static-simultaneous presentation formats used so far yield similar performance as dynamic visualizations, because the pictures remain visible all the time or because their spatial arrangement facilitates mental animation. Hence, in Study 1b we compared dynamic visualizations to three additional variants of static-simultaneous ones, namely to column, matrix, and circle presentations (Figure 1).

When depicting pictures in columns comparisons have to be made from upper to lower positioned pictures or vice versa. This spatial layout may yield the advantage that at least for pictures presented in a landscape format the distance between to-be-compared elements in two pictures is smaller. Hence, shorter saccades are required. Moreover, for the current task the elements that need to be compared to each other to determine their relative position (i.e., the fins) and thus to infer the locomotion pattern from it are vertically aligned. Hence, only few visual search processes are needed. On the other hand, this arrangement corresponds neither to the reading order nor to the objects' moving direction. In Study 1b we additionally implemented a matrices presentation of the pictures, where horizontal as well as vertical processing was needed. Finally, the circle presentation took into account that the depicted locomotion patterns are cyclic (i.e., reiterating) so that the last picture of one movement cycle automatically leads to the beginning of a new cycle without forcing the learner to skip back to the beginning of the row or column.

The question of how different spatial layouts of static-simultaneous visualizations influence their effectiveness compared to dynamic visualizations was investigated in Study 1b. If dynamic visualizations were superior to these static-simultaneous variants, this would indicate that the row presentation format used earlier is advantageous because of its specific spatial layout and not just because the pictures are permanently visible, which is also true for the other static-simultaneous variants.

The Role of Spatial Ability

In line with prior research we considered learners' spatial ability as a possible moderator of the effectiveness of dynamic and static visualizations during learning (e.g., Boucheix & Schneider, 2009; Hays, 1996). Hegarty (1992) proposed that learners' spatial ability plays a role for the process of mental animation. Moreover, Hegarty and Sims (1994) showed that high spatial ability learners outperformed low spatial ability learners in mechanical mental animation tasks. Furthermore, Hays (1996) showed 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 (Hegarty & Waller, 2005). Whereas low spatial ability learners suffer from "poor" instructions, high spatial ability may compensate for such instructions (cf. ability-as-compensator hypothesis, Mayer & Sims, 1994; see also Boucheix & Schneider, 2009). Accordingly, for the current study benefits in favour of dynamic visualizations (and potentially, static-simultaneous-rows visualizations) should be more pronounced for low rather than for high spatial ability learners.

Hypotheses

For *Study 1a*, in which we addressed the temporal aspects of static visualization formats, we assumed that dynamic visualizations would be superior to static-sequential visualizations, but not to static-simultaneous visualizations presented in rows, thereby replicating findings form earlier studies with a broader range of recognition tasks and more standardized visualizations (see below). In *Study 1b* we tried to further disentangle temporal and spatial aspects of presenting multiple static pictures by testing whether dynamic visualizations would be superior to other static-simultaneous presentation formats. We assumed that dynamic visualizations would show stronger advantages in this case, thereby suggesting that the benefits of static-simultaneous visualizations presented in rows are not just due to temporal aspects but also due to their spatial layout.

For both studies, we assumed that higher spatial ability would be associated with better learning outcomes than lower spatial ability. Moreover, we proposed that learners with lower spatial ability would benefit stronger from learning with dynamic visualizations compared to static visualizations than those with higher spatial ability.

Study 1a

Method

Participants and Design. We randomly assigned 75 university students (average age: 24.48 years, *SD* = 4.34; 53 female) to one of three visualization conditions: dynamic vs. static-sequential vs. static-simultaneous-rows.

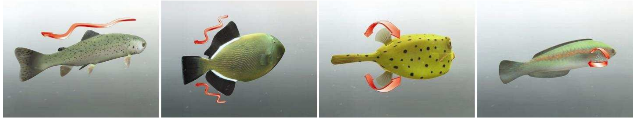

Figure 1: The four to-be-learned locomotion patterns (relevant movements indicated by arrows).

Materials. Participants were asked to learn how to classify fish according to their locomotion patterns based on visualizations that illustrated four different locomotion patterns. 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; cf. Figure 1). 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 varied the *presentation format* of the visualizations as independent variable. Dynamic representations were compared to nine either sequentially or simultaneously (in rows) presented static visualizations.

We developed highly realistic 3D-models of fish performing the four to-be-learned locomotion patterns based on which 2D-animations were rendered that were standardized in terms of the perspective, the background and the position of the fish. These animations were used as dynamic learning materials. The static pictures were extracted from these animations by an expert and represented the key states in the movement cycles.

In the *dynamic condition* the movement cycles of the locomotion patterns were presented in loops in the animations (72 s per locomotion pattern). In the *static-sequential condition* the nine static pictures were presented twice successively for 4 s each. In the *static-simultaneous-rows condition* the same pictures were presented in parallel for 72 s. They were arranged in two rows corresponding to the two phases of the locomotion patterns (cf. Figure 2, upper left part). 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' size was half of the size of the dynamic and the static-sequential conditions. There was no need for the subjects to scroll the page.

During learning the participants saw visualizations for each of the four to-be-learned locomotion patterns in a predefined order. The presentation was system-controlled and accompanied by narration. The narration explained the locomotion pattern in terms of typical fish using this locomotion pattern, body parts involved, kind of movements executed (undulation versus oscillation), parameters of the movements (e.g., amplitude), and maximum velocity.

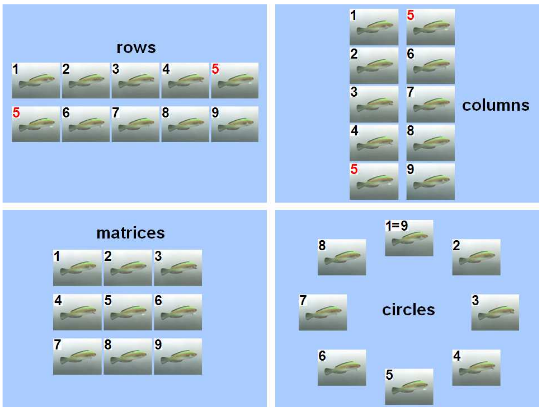

Figure 2: Static-simultaneous presentation formats.

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

To assess learning outcomes a locomotion pattern recognition test consisting of pictorial multiple-choice items was administered. Underwater videos of real fish performing one of the four locomotion patterns were used as test stimuli. The number of test items was constrained by a number of aspects (e.g., resolution, visibility of the fish from a certain perspective, clear depiction of the respective locomotion patterns). For each of the four locomotion patterns seven videos were identified. 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 3). 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, intermediate, and high task difficulty. Their decisions were based on the visibility of the relevant parts used for propulsion as well as on the absence or presence of miscellaneous movements of the fish’s body parts that could have been mistaken as being relevant for propulsion (e.g., movements only necessary for navigational purposes). Videos that showed the pattern relevant for propulsion continuously and contained no other movements were assigned a low task difficulty (8 items). Videos that showed the pattern relevant for propulsion continuously, but contained movements similar to another locomotion pattern were assigned an intermediate task difficulty (11 items). Videos that either showed the pattern relevant for propulsion continuously, but contained additional movements similar to at least two other locomotion patterns or videos that did not show the relevant propulsion pattern continuously or that did show it in a non-salient manner (whereby all of these videos contained movements similar to at least one other locomotion pattern) were assigned a high task difficulty (9 items). Five cases of disagreement between the two experts were resolved by negotiation.

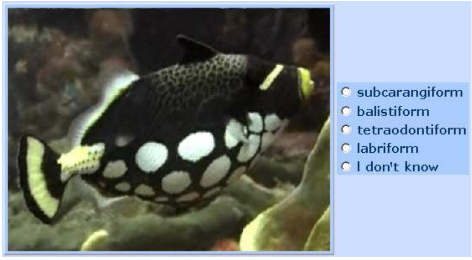

Figure 3: Screenshot of a recognition test example item.

Procedure. After completing paper-based the MRT, PFT, and a demographic questionnaire, participants read an introduction, which was followed by the computer-based learning phase. Finally, learners worked on the computer-based pictorial recognition test.

Results

Performance in the three recognition subtests was analyzed by a MANCOVA with presentation format (dynamic vs. static-sequential vs. static-simultaneous-rows), the MRT, and the PFT as independent variables (Table 1).

There was an overall effect for presentation format (F = 2.28, p = .04) and for the PFT (F = 3.62, p = .02), but no other main effect or interactions. There was an effect for presentation format only for recognition tasks with an intermediate difficulty (F = 4.00, p = .02). Dynamic visualizations were superior to static-sequential visualizations, but not to static-simultaneous-rows visualizations. Higher performance in the PFT was associated with better recognition for tasks with low (F = 7.52, p < .01) and intermediate difficulty (F = 9.18, p < .01).

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

	Presentation Format		
Task Difficulty	dynamic (n = 25)	static-sequential (n = 25)	static-simultaneous-rows (n = 25)
low	92.65	84.58	86.43
	(3.90)	(3.88)	(3.93)
intermediate	87.83	71.85	74.30
	(4.33)	(4.30)	(4.36)
high	71.80	72.67	74.36
	(4.57)	(4.55)	(4.61)

Discussion of Study 1a

The results confirmed that dynamic visualizations are better suited to convey knowledge about the continuity of locomotion patterns compared to static-sequential visualizations, but not to static-simultaneous visualizations presented in rows – at least for recognition tasks with an intermediate difficulty level. These findings hence replicate those of a former study, where digital underwater videos as well as black-and-white animated line drawings were used as dynamic visualizations (Imhof et al., 2009). Hence, the results obtained by Imhof et al. were not an artefact of either low visibility of important kinematical aspects in the underwater videos or their potentially oversimplified representation in the animated line drawings, because the visualizations in the current study were of high quality in terms of the visibility and fidelity of important features.

In sum, the results suggest that dynamic visualizations as well as static-simultaneous-rows presentations allow for the construction of an adequate mental representation of kinematics; however, it is yet not clear whether the relative good performance of the latter condition is due to its temporal (permanent visibility) or its spatial aspects (rows), which is why Study 1b was conducted.

Study 1b

Method

Participants and Design. We randomly assigned 75 university students (average age: 23.35 years, SD = 3.71, 57 female) to three static-simultaneous conditions, namely a static-simultaneous-columns, a static-simultaneous-matrices, and a static-simultaneous-circles condition, to compare their performance to that of students in the dynamic visualization condition of Study 1a.

Materials. The learning domain, the measures as well as the procedure were identical to Study 1a. In the *static-simultaneous-columns condition* the single pictures were arranged in two columns corresponding to the two phases of the locomotion patterns (cf. Figure 2, upper right part). To facilitate the transition between the left and the right column the fifth picture was depicted twice, once as the last picture of the left column and once as the first picture of the right column. In the *static-simultaneous-matrices condition* the nine pictures were presented in 3x3 matrices, ordered primarily from left to right and secondarily from top to bottom (cf. Figure 2, lower left part). Contrary to the static-simultaneous-rows and the static-simultaneous-columns condition no pictures were depicted twice. In the *static-simultaneous-circles condition* the single pictures were presented in a clockwise arrangement with the first picture at the 12 o'clock position (cf. Figure 2, lower right part). In this condition the ninth picture was not presented, because it depicted the same state in the locomotion pattern as the first picture. The pictures in all conditions had the same size as those in the static-simultaneous-rows condition in Study 1a.

Results

Performance in the three recognition subtests was analyzed by a MANCOVA with presentation format (static-simultaneous-columns vs. static-simultaneous-matrices vs. static-simultaneous-circles vs. dynamic), the MRT, and the PFT as independent variables (Table 2).

There was an overall effect for presentation format (F = 2.64, p = .01), for the MRT (F = 4.93, p < .01) and for the PFT (F = 2.82, p = .04), but no interactions. There was an effect for presentation format for recognition tasks with low (F = 4.01, p = .01) and intermediate difficulty (F = 6.41, p = .001). Dynamic visualizations led to better recognition for tasks with low difficulty compared to the static-simultaneous-matrices visualizations as well as for tasks with intermediate difficulty compared to all three static-simultaneous conditions. Moreover, higher performance in the MRT was associated with better recognition performance for tasks with low (F = 4.55, p = .04) and intermediate difficulty (F = 14.59, p < .001). Furthermore, higher performance in the PFT was associated with better recognition for tasks with low difficulty (F = 4.63, p = .03).

Discussion of Study 1b

None of the additionally tested spatial layouts of the static-simultaneous visualizations achieved the same recognition performance as the dynamic visualizations for tasks with an intermediate level of difficulty. For recognition tasks with a low level of difficulty we found dynamic visualizations to be superior to static-simultaneous visualizations presented as matrices, showing that this presentation format bears the fewest of all advantages for the task at hand.

The possible advantage of a circular presentation that it adequately represents the cyclic nature of the locomotion patterns might have been cancelled out by the fact that with this presentation format the orientation of the pictures interfered with the swimming direction of the fish. That is, for pictures presented in-between the 3 o'clock and the 9 o'clock position, the next picture is depicted to the left of its previous picture, whereas the swimming direction of the fish still indicates a movement from left to right. Moreover, contrary to the assumption that the spatial contiguity in a column supports the visual alignment of to-be-compared elements and hence might facilitate mental animation, this condition was not any better than the dynamic condition.

In sum, the results suggest that dynamic visualizations are superior to different static-simultaneous presentation formats as long as the spatial layout of the static pictures does not support mental animation processes in a way that corresponds to our reading/viewing behavior and that is in line with the moving direction of the depicted object.

Table 2: Adjusted means (and standard errors) for recognition performance (in % correct) as a function of presentation format and task difficulty (Study 1b).

	Presentation Format			
	static-simultaneous			dynamic
Task Difficulty	columns (n = 25)	matrices (n = 25)	circles (n = 25)	(n = 25)
low	83.85 (4.13)	72.40 (4.47)	79.21 (4.07)	92.78 (4.36)
intermediate	70.26 (4.20)	63.65 (4.55)	66.90 (4.14)	88.36 (4.43)
high	66.69 (4.76)	62.58 (5.16)	61.52 (4.70)	71.77 (5.02)

General Discussion

The superiority of dynamic visualizations over most static presentation formats for learning tasks that explicitly require the identification of the continuity of movements and involve a strong perceptual component was supported in Studies 1a and 1b. However, consistent with prior findings (Boucheix & Schneider, 2009; Imhof et al., 2009) a static-simultaneous presentation of multiple pictures in rows led to the same performance as the dynamic visualizations. Accordingly, for this specific case where the moving direction of the depicted object and the spatial layout of the pictures correspond to each other, learners seem to be well able to mentally animate the sequence of pictures and hence to infer the kinematics from it (Hegarty, 1992). However, this result pattern holds true only for tasks of intermediate difficulty. The fact that we did not find the same results for tasks of low difficulty can be explained in terms of a ceiling effect. The items are maybe so clearly identifiable that learners from all experimental conditions (except for the matrices condition in Study 1b) achieved very good results. According to the expert opinions there were always at least two concurring patterns visible in items with high task difficulty. Which one of these is used for propulsion cannot be answered only on the basis of perceptual input. Rather conceptual knowledge acquired from the spoken explanations, which were identical in all experimental conditions, had to be used to answer these items. Additional design techniques like cueing (De Koning et al., 2009) or enriching static displays (Münzer, Seufert, & Brünken,

2009) could further enhance the effectiveness of static-simultaneous presentation formats.

Astonishingly, there was no moderating effect of spatial ability concerning the effectiveness of different presentation formats of visualizations. Therefore, the assumed ability-as-compensator hypothesis could not be confirmed. In further studies this issue should be addressed in more detail, because there is an ongoing discussion about the separate components that make up the construct spatial ability (for an overview see Hegarty & Waller, 2005). Especially, the dynamic spatial ability component might be a relevant dimension for mental animation in dynamic tasks (D'Oliveira, 2004; Hunt et al., 1988). Hence, it might be that the tests used here may not have addressed those spatial ability components that might be most relevant to mental animation, even tough they are commonly used in visualization research. Despite of these doubts concerning the validity of the measures used, we were nevertheless able to show that irrespective of visualization format higher spatial ability was associated with better learning outcomes than lower spatial ability for tasks with low and intermediate difficulty, thereby replicating the findings of Hegarty and Sims (1994). Hence, we can at least conclude that spatial abilities are relevant to the task at hand. Nevertheless, further studies need to address the question of how mental animation from static-simultaneous visualizations supports learning.

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