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Exploration vs. limitation – An investigation of instructional design techniques for spatial ability training on mobile devices

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A R T I C L E I N F O

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A B S T R A C T

Spatial abilities and thus mental rotation skills predict achievement in STEM domains. Thus, a wide range of studies investigated the possibilities and trainings of mental rotation skills. One prominent approach is using different digital tools and representation formats to foster spatial abilities. Thereby numerous studies analyzed effects of static in comparison to interactive dynamic representations of mental rotation tasks using different types of interactions. Although the use of dynamic representations is discussed critical regarding superficial information processing, there are no studies to date varying instructional techniques in interactive dynamic spatial trainings. In two studies we compared *Limited Rotation* training to non-limited *Free Rotation* training with high school students ($N_{pilot} = 21$, $N_{main} = 66$). Results after training show a superior effect of the limited compared to the non-limited training regarding the students' success rate, but not their motivation and mental demand. Additionally analyzed process data show more efficient ways of task solving after limited rotation training indicated by reduced response time and rotation way accompanied by higher success rates in solving non-limited rotation tasks. Results of a pre-and-post-comparison of mental rotation skills indicate a higher increment after limited rotation training. Over-facilitating effects of dynamic representations are discussed.

1. Introduction

Spatial abilities are very important for successful performance in many different domains, such as in music and sports (Pietsch & Jansen, 2012) as well as in science, technology, engineering, and mathematics (STEM) domains (Newcombe, 2010; see DeSutter & Stieff, 2017) and in everyday life (Halpern et al., 2007; Uttal et al., 2013; Wai, Lubinski, & Benbow, 2009). Specifically, mental rotation – the ability to spatially rotate 2D or 3D figures in mind (Linn & Petersen, 1985) – plays a crucial role in STEM disciplines. Mental rotation often involves tasks which demand processes of dynamically representing and spatially transforming figures in mind. Similar processes are often required across STEM disciplines, for example, when solving geometric problems, understanding molecular structures in chemistry, or reading maps in geography (Maeda & Yoon, 2013; Rodán, Contreras, Rosa Elosúa, & Gimeno, 2016). Given the overlap between the processes involved in mental rotation and learning STEM subjects, Uttal et al. (2013) have suggested that the training of spatial abilities can lead to an increase in students' performance in STEM subjects. In fact, there is emerging empirical support that training spatial abilities contributes to adults' performance in STEM (Uttal & Cohen, 2012). However, at present there is relatively less attention for promoting and training spatial abilities in elementary and secondary schools, also in comparison to similarly important verbal and mathematical abilities (Colangelo, Assouline, & Gross, 2004; DeSutter & Stieff, 2017). The present study is focusing on the training of mental rotation abilities by addressing the advantages of mobile devices, specifically the options to represent objects interactively and dynamically. Interactive dynamic representations are common in everyday life. In this study interactions are characterized by direct touch-control over the displayed objects on mobile devices. Dynamic representations in the present study show procedures of rotations. The combination of interaction and dynamic representation allows learner to rotate 3D-objects of typical mental rotation tasks on the surface of a 2D-mobile device. The present two studies analyze the efficiency of two kinds of interactions in a digital spatial ability training: free unlimited rotation to facilitate mental processes and limited rotation to trigger the

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effortful use of mental resources for task solving

1.1. Direct interaction and learner control

Interaction with objects on mobile devices – specifically direct touch-based interaction – is seen to cause processing benefits related to direct interaction and learner control. Studies revealed that direct interaction increases the guidance and focus of attention near the hand (Abrams, Davoli, Du, Knapp, & Paull, 2008; Cosman & Vecera, 2010) and support a deeper cognitive processing of information (Reed, Grubb, & Steele, 2006). Tracing the elements of paper-based geometry examples with the index finger was shown to be beneficial in reducing the number of errors made, reducing the perceived difficulty during learning, and reducing response time (Hu, Ginns, & Bobis, 2015). Additionally, it was revealed that students who directly traced the learning material on paper outperformed those tracing above the paper. This suggests that the physical interaction with the learning material plays an essential role to produce learning effects. Moreover, direct interaction often also implies a high degree of learner control over interactively controllable representations. Such interactive representations allow learners to adapt the task to their individual cognitive processing needs. Technical variants to realize interactivity range from the simple stop and forward mechanisms when watching educational video to the touch-based control of pictures, animations and texts on a 2D-mobile device and further to the manipulations of 3D-objects via data gloves in virtual reality. A considerable number of studies have revealed that various formats of learner control and interactivity with educational media yield higher motivation, improve learning performance, and reduce cognitive load (Scheiter, 2014; Schwan & Riempp, 2004).

1.2. External dynamic visualizations and facilitation effects

The efficiency of external dynamic visualizations – without the possibility of interactions – was shown by a meta-analysis by Höffler and Leutner (2007) which revealed a general learning advantage of dynamic visualizations (animations) over static visualizations. This effect was even more pronounced when procedural-motor knowledge had to be acquired and when non-interactive dynamic representations were highly realistic (e.g. animation, video). It is argued that non-interactive dynamic representations at least partly supplant the intended internal cognitive processes that learners have to engage in (Salomon, 1994). It is moreover argued, that this kind of supplantation causes a facilitating effect regarding the processing of the learning material (Münzer, Seufert, & Brünken, 2009; Schnotz & Rasch, 2005). One can argue, that, if the facilitating effect holds true, learners might invest the freed-up resources to deeper process the task and thereby to improve performance. To the contrary, critical approaches state that the facilitation caused by supplantation through the dynamic representations reduces the depth of information processing and results in reduced understanding and/or acquisition of skills. A similar approach is also reflected in the *Illusion of Understanding* model by Paik and Schraw (2013), which describes that the addition of dynamic representations (e.g. animations) to multimedia presentations can affect metacognitive monitoring, this is, learners may perceive the learning material to be easier to understand and develop more optimistic metacomprehension. In consequence, less cognitive effort when learning with animation is invested and may lead to decreased knowledge acquisition. Additionally, a later meta-analytic review by Höffler (2010) revealed that especially low-spatial ability learners benefit from learning with dynamic and 3D-visualizations. The authors argued that dynamic – in this case non-interactive – representations incorporate a compensating function that enables low spatial-ability learners to easier understand and process procedural pictorial information. At this, animations are seen to reduce the cognitive load imposed on the limited resources of the working memory while acquiring new knowledge or solving problems (Lowe & Schnotz, 2014; Sweller, Ayres, & Kalyuga, 2011). Although a training with spatial tasks is not completely similar to a typical learning task of complex concepts like inferring a cross-section of an unfamiliar 3D object with a complex internal structure (Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2008), the supplantation of internal cognitive processes should also hold true for manipulation of objects while solving spatial tasks (e.g., mental rotation, spatial orientation, perspective taking).

1.3. Interaction types and training of spatial abilities

In the case of mental rotation training, numerous studies have used this combination of learner control via technical devices and dynamic representations. The studies used different technical devices and interaction types to support the process of solving mental rotation tasks. Especially interactive dynamic representations of tasks can be helpful for learners with difficulties in solving spatial task. This is due to interactivity and learner control, e.g. the learners' possibility to adapt the pacing of the external dynamic visualization of the task to specific needs of her spatial processing system.

A key question for digital spatial abilities training concerns the design of a training which might be helpful in fostering mental rotation skills. This question has so far been addressed by numerous empirical studies, which applied several training designs to support mental rotation (DeSutter & Stieff, 2017; Reilly, Neumann, & Andrews, 2017). Over the last years, an increasing number of these training studies used visual representations on digital devices that allowed learners to manipulate virtual 2D- or 3D-objects via different types of interactions.

Gardony, Taylor, and Brunyé (2014a) concentrated on differences and similarities of solving static (e.g. mental) or interactive, dynamic (e.g. physical) rotation tasks, which were controlled by a rubber ball with built-in tilt sensors. They found higher response times and higher success rates with the interactive dynamic rotation task format compared to the static tasks. To examine strategy differences while solving rotation tasks within different interaction formats Boucheix and Chevret (2014) compared static mental rotation tasks with non-interactive animated (dynamic) rotation task, and with interactive dynamic tasks, that were controlled by the learner via computer mouse. They ascertained no effects on the participants' performance but found the highest response time for interactive dynamic tasks in the mouse-controlled condition. Zander, Wetzel, & Bertel (2016) used touch-based interaction on a tablet computer to investigate the efficiency regarding effort and success of interactive, dynamic compared to static rotation tasks. Their study discovered better performance on mental rotation after solving interactive dynamic tasks, but no difference in reverse. All three of these studies investigated the differential effects of interactive dynamic and static task presentation in regard to success rate, response time, and effort. However, none of them implement longer training sessions to foster the participants' rotation skills.

Wiedenbauer and Jansen-Osmann (2008) used 2-dimensional images presented on a computer screen that could be rotated via a knob placed in front of the participants to train mental rotation skills. They found lower response times for mental rotation tasks after the training sessions, but there were no differences in the participants' performance compared to participants without a specific spatial training. Adams, Stull, and Hegarty (2014) concentrated on the training of solving rotation tasks via static and interactive dynamic tasks. Interactivity was realized by a 3 degree-of-freedom rubber ball. They found lower response times for interactive dynamic tasks after the interactive dynamic training as well as lower response times for static tasks after static and interactive dynamic training compared to a control group. Ha and Fang (2018) investigated the training of mental rotation via interactive dynamic rotation of real objects with built-in tilt sensors and virtual representatives. In their study, they revealed higher success rates for static tasks after the interactive dynamic training. Together, all these studies found beneficial effects of trainings with static as well as interactive dynamic rotation tasks for the participants' performance and response time. However, most of the described studies either compared static and interactive dynamic representations of rotation stimuli directly in regard to success rates and response times (Gardony, Taylor, & Brunyé, 2014a) or investigated the transfer from interactive dynamic rotations to solving static tasks and vice versa during a single experimental session (Adams, Stull, & Hegarty, 2014; Wiedenbauer & Jansen-Osmann, 2008; Zander, Wetzel, & Bertel, 2016).

1.4. Activating mental processes by rotation limitations

Until now, it is still unclear what the mental rotation training's success is based on. Especially, since interactive dynamic tasks might incorporate the problem of "too much" support over the course of time. The study by Boucheix and Chevret (2014) is relevant in this regard as it reveals that, other than observable animated and static representations, the dynamic representation of 3D-objects induces strategies of comparing shapes via stepwise external rotation instead of rotating objects in mind. This finding indicates that possibly the deeper, intended cognitive process of mentally rotating task-relevant blocks is not really supported by interactively rotating 3D-objects on a screen. Rather, less loading, superficial perceptual strategies (e.g. comparing shapes) are applied (for a shift to perceptual processes and facilitation effect see also Münzer et al., 2009). This can be interpreted as a hint that the pure facilitating support of mental rotation via dynamic rotation might not help in the training of rotation processes in mind.

In consideration of this problem, it rather might be necessary to encourage the use of cognitive resources – *activating effect* – for producing internal (mental) rotations. A possibility to realize an activation of mental resources while using dynamic representations is the implementation of tools typically integrated in digital games, such as time or other resource limitations that trigger cognitive stimulation (Blohm & Leimeister, 2013). A basic and easy to apply method thereby is to display the status of resources and the connected processes of loading or reduction of the resources in dependence of learner's actions in the game (Björk & Holopainen, 2005; Koch, Ott, & Oertelt, 2013). This can simply be realized by a progress bar, which visualizes the decreasing status of the corresponding resource.

Following this line of argumentation, the present study compares a non-limited *Free Rotation* version of an interactive dynamic task against a restricted interactive dynamic version of the same task: This *Limited Rotation* version contains a progress bar that displays the decrement of "rotation energy", e.g. the possible amount of rotation way left to solve a task. The aims of our study are to analyze the long-term effects of rotation training with limited and non-limited rotation processes and to analyze training effects not only in terms of success rate, which previous studies primarily focused on, but also in regard to mental demand and frustration as well as to process-oriented measures of rotation behavior. Additionally, none of the studies discussed above examined gradations, instructional design techniques (e.g. fading of support) between static and freely rotatable dynamic tasks. The present study therefore investigated the effectiveness of a digital spatial abilities training focused on improving mental rotation skills by using a stepwise fading of support via the limitation of possible rotations.

2. Aims and research question

Based on the argumentation developed above, it is yet an open question (1) if and to what extent interactive dynamic representations facilitate mental rotation over a longer period of time, and (2) whether the interactive dynamic representations of rotation tasks should be combined by activating instructional methods (such as the *Limited Rotation* that restricts interactions) that encourage learners to rotate objects internally so as to gain increments in mental rotation performance.

To address these issues, we used the iPad app *Rotate It!* The app enables learners to interact with 3D-objects (Shepard & Metzler, 1971) via touch gestures in a non-limited – *Free Rotation* – condition, which allows to explore the shape and orientation of objects in their own manner (see Fig. 1, for further explanations see Zander, Wetzel, & Bertel (2016). Additionally, in another version of the app we integrated an inverted progress bar. As displayed in Fig. 1, the progress bar displays the status of remaining physical interaction possibilities (referred to as remaining rotation way). The load of the progress bar decreases with every rotation, at the same time the decrement can be observed easily. When the progress bar is emptied, physically interacting with the objects is not available anymore and the remaining task has to be solved mentally. As introduced before, the *Limited Rotation* was implemented to prevent learners from a simple offloading of mental processes to the external dynamic representation.

Based on our research aims we postulate the following hypotheses.

Hypotheses 1a & 1b – Success rate: The *success rate* reflects the percentage of tasks that were solved correctly by each participant. For the *Free Rotation* version of the training, we assume only small, if any, gains in *success rates* after training compared to before training. This expectation is based on the *facilitating effect* of dynamic representations (e.g. offloading, supplantation) as described above. Due to the expected *activating effect* of the limited rotation, we assume that after training with the *Limited Rotation* version students would show higher *success rates* while solving both dynamic (H1a, based on tasks presented in *Rotate It!*) or static (H1b, based on the *Cube Comparison Test*) 3D-mental rotation tasks compared to the *Free Rotation* group.

Hypothesis 2 – Mental demand: Due to the expected increment of mental rotation skills during the *Limited Rotation* training, the reported *mental demand* should be decreased from before to after training. For the *Free Rotation* group, we expect a similar, but not as pronounced decrement of the participants' mental demand as they practiced the same kind of task in previous sessions.

Hypothesis 3 - Frustration: The same reasoning applies to affective states: from before to after training, the expected mental rotation improvements should be evidenced also in terms of less negative affective states, specifically *frustration*, in the *Limited Rotation* training compared to the *Free Rotation* training. On the contrary, we expect no changes in the *Free Rotation* group from pre-to post-training.

Next to performance and motivational measures, we also investigated whether differences between groups before and after the training showed up on indicators for rotation behavior before and after the training. As software used on digital devices allow for the tracking of manual interactions, the following indicators of rotation behavior were recorded: *Rotation way* measures in degrees how far a student rotated an object across an entire task irrespective of rotation direction. *Number of drags* states the tally of any finger movement, as counted between setting the finger down on the tablet screen and taking it up again. *Response time* measures the time in seconds, the participant needs to solve each task, more precisely the time span between starting the task and giving the answer. *Net rotation time* measures the time the students are manually interacting with the objects. The variable *time until first drag* states the time stamp, the students start to move the stimuli via touch-gestures after a task is presented.

Hypotheses 4a - 4e – Rotation behavior: Due to the triggered use of mental resources before training and while solving the tasks in the *Limited Rotation* group but not in the *Free Rotation* group, results are expected to reveal the following pattern of results:

- For *response time* we expect only small gains in regard to the time spent per task for the *Free Rotation* training. In contrast, we expect that after training with *Limited Rotation* - compared to *Free Rotation* - students would show less time spent per task while solving dynamic rotation tasks. (H4a)
- *Net rotation time* is expected to be reduced in the *Limited Rotation* group from before to after the training, as solving the tasks mentally is trained more focused through the enforcement in *Limited Rotation.* In the *Free Rotation* group, no such explicit changes are expected. (H4b)

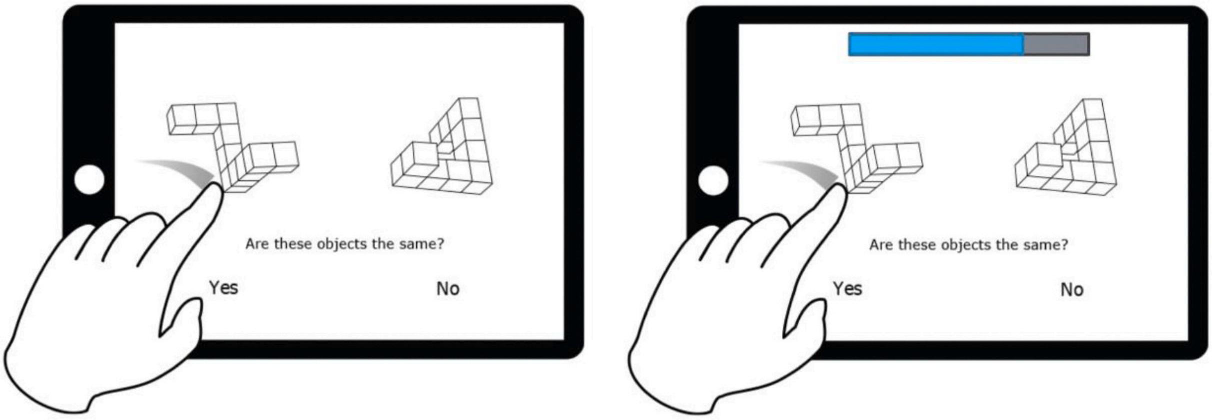

Fig. 1. Visualization of the touch-based interaction in the *Rotate It!* App – Left: in *Free Rotation*; right: with *Limited Rotation*.

- *Time until the first interaction* with objects is an indicator for pre-processes of planning and starting mental rotation before starting interactions. The application of a limiting progress bar is expected to show an *activating effect*, meaning that the *rotation restrictions* trigger active use of mental resources. Therefore, we assume *time until first drag* to increase from before to after training in the *Limited Rotation* group due to triggered mental processes. No comparable changes are assumed for the *Free Rotation* group. (H4c)
- *Rotation way* as an indicator of external rotations is expected to decrease in the *Limited Rotation* group from before to after training and subsequently to be reduced after training compared to *Free Rotation* training. Again, for the *Free Rotation* group no to slight decrements in rotation way before and after training are assumed. (H4d)
- *Number of drags* is an indicator as well for touch-interactions that are used to control changes and rotations of the dynamic representations. It is expected to be reduced in the *Limited Rotation* group from before to after training and to be lower in the *Limited Rotation* group compared to the *Free Rotation* group after training. (H4e)

The above hypotheses are tested in the main study presented in this article. Before reporting on the main study, we first describe a pilot study in which we aimed to assess the appropriateness of the restriction levels regarding *success rates*, *mental demand*, and *frustration* that we would use for the age group targeted in the main study. In previous work, we also investigated rotation interactions for 9-to-10-year-olds (Zander, Wetzel, & Bertel, 2016), but given that in the present study we extended this to 15-to-16-year-olds to prevent problems with the understanding of instructions and task affordances experienced (Hoyek, Collet, Fargier, & Guillot, 2012), we piloted the materials for the age group targeted in the main study.

3. Pilot study

3.1. Study design and participants

Twenty-two secondary school students, aged 15 or 16 years from different schools in Germany participated in this study. Due to a student's illness, complete data sets of only 21 students ($N_{female} = 11$, mean age: 15.38 years) were gathered and analyzed. Prior to experimentation, informed consent was sought and obtained from parents and school authorities. Three levels of the rotation limitation were tested as within-subjects factor: An unrestricted *Free Rotation* condition and two *Limited Rotation* conditions with 250% and 200% available rotation way relative to the initial angular disparity of each task's objects. The limitation levels were based on the descriptive rotation data of prior studies (Bertel, Wetzel, & Zander, 2017; Zander, Wetzel, & Bertel, 2016).

Each condition consisted of 60 tasks resulting in a total of 180 tasks that were solved by each student. To enable cross-study comparison, we used the same set of stimuli as Gardony, Taylor, and Brunyé (2014a), which was originally taken from the library by Peters and Battista (2008). The initial angular disparity of the stimuli ranged between 0° and 180° in steps of 6° in each task set. The tasks were presented in randomized order. Before each session, each participant solved five exercise tasks to familiarize themselves with the kind of task and the actual rotation limitation level. Participants were instructed to work as quickly and precisely as possible and did not receive feedback during tasks. After each session, participants answered questionnaires on *mental demand* and *frustration*.

3.2. Measures

After each session students had to assess the tasks' mental demand and their level of frustration on two scales ranging from 0 (Very Low) to 20 (Very High). These scales were based on the appropriate subscales of the Raw Task Load Index, an unweighted version of the NASATLX questionnaire (Hart & Staveland, 1988). Additionally, we tracked each participant's *response time*, *success rate*, and rotation behavior, that was subsequently aggregated into the variables *rotation way*, *number of drags*, *net rotation time*, and *time until first drag*.

3.3. Results

In the following, results from the multivariate analysis of variance (MANOVA) as well as univariate and single effects are reported on the gathered measures. Session and, associated therewith, the limitation level, were the within-group factors in these analyses. In all analyses, we used Pillai's trace and Greenhouse-Geisser correction, the alpha-level was set to .05, and Bonferroni correction was applied to all single comparisons.

3.3.1. Measures on performance and motivation

Table 1 provides an overview of means and standard errors of the dependent performance variables for all three conditions. Descriptive

Table 1
Means and standard errors (in brackets) for all dependent variables in the different within-subjects conditions.

	Free Rotation	Limited Rotation – 250%	Limited Rotation – 200%
Success rate (%)	0.911 (0.023)	0.907 (0.019)	0.889 (0.023)
Mental effort	9.52 (0.93)	10.00 (1.05)	10.71 (1.09)
Frustration	5.43 (1.13)	3.86 (0.66)	5.67 (1.13)

data showed that the expected decrements of *success rate* and increments of *mental demand* and *frustration* due to restrictions of rotation way are in the expected direction although either small (*success rate* and *mental effort*) or non-systematic (*frustration*). This was confirmed in a MANOVA over all three sessions for the variables *success rate*, *mental demand*, and *frustration*, which revealed no significant differences, $V = 0.400$, $F(6, 15) = 1.667$, $p = .197$. Together, these results indicate that the applied rotation restrictions have not proven suitable to gain changes in measures on performance and motivation.

3.3.2. Measures on rotation behavior

Table 2 displays the means and standard errors for the process-based indicators for rotation behavior in relation to the limitation levels. The MANOVA revealed a significant effect of the independent within-group factor *Session* considering the dependent process-based indicators of rotation behavior, $V = 0.933$, $F(10, 11) = 15.379$, $p < .001$. Subsequent univariate tests revealed significant effects on the dependent variables *rotation way*, $F(1.01, 20.20) = 52.145$, $p < .001$, *number of drags*, $F(1.15, 22.92) = 16.203$, $p < .001$, $\eta_p^2 = 0.448$, *net rotation time*, $F(1.08, 21.664) = 51.635$, $p < .001$, $\eta_p^2 = 0.721$, and *time until first drag*, $F(1.66, 33.20) = 26.530$, $p < .001$, $\eta_p^2 = 0.570$, all in the expected direction, indicating that *rotation way* and *net rotation time* decrease with the increment of rotation limitations and *time until first drag* increases with harder limitations. This supports our assumptions of the way the limited rotation should affect learners' rotation behavior. Assumptions hold not true for *response time*, $F(1.48, 29.57) = 0.755$, $p = .441$, $\eta_p^2 = 0.036$.

Additional single comparison tests within the different restriction levels (see Table 2) support these findings, revealing that rotation way, number of drags, and net rotation time differ significantly in all paired combinations of the three rotation restrictions. A closer look at rotation way demonstrates these restrictions: While the students rotated 522.88° on average in the free rotation condition, the mean values decreased to 106.52° for the 250% limited rotation and to 61.72° for the 200% limited rotation. Also, the mean values of number of drags and net rotation time decreased to significantly lower levels during the restricted conditions, with lower values in more restricted conditions. Descriptive data for time until first drag revealed that the mean time before the student's first interaction falls below 1 s in the free rotation condition, while time until first drag then rises during the 250% and 200% restriction, which indicates the initiation of a more strategic, deliberated use of mental resources before the actual rotation. At this, the expected pattern was proven significant (see Table 2).

In summary, data of the pilot study support our assumptions regarding the effects of the restriction levels in regard to central indicators of rotation behavior: *rotation way*, *number of drags*, and *net rotation time*. However, mental processes and affective state under the applied rotation restrictions were not affected, the same holds true for *time until first drag*. Based on this, we decided to set the rotation limitations even more restrictive in the main study.

4. Main study

In the main study, we tested the *Limited Rotation* training compared to a *Free Rotation* training to examine whether the *Free Rotation* training causes mainly *facilitating effects* while the *Limited Rotation* training might enhance performance by an *activating effect*. Compared to the pilot study, a mental rotation test (*Cube Comparison Test*, Ekstrom, French, Harman, & Dermen, 1976) was included into the study design before the actual training phase to control for individual differences and to allocate students equally to both experimental conditions depending on their spatial abilities. Additionally, gender was considered to ensure an equal distribution of male and female students to the experimental conditions. Moreover, due to relatively high success rates in the pilot study, we decided to test a slightly younger group of students.

4.1. Participants

Ninety secondary school students aged between 11 and 13 from a school in Germany participated in the study. Before starting the main study, informed consent was sought and obtained from parents and school authorities. For our final analysis complete datasets of 66 students ($N_{female} = 43$, mean age: 12.27 years) who participated at all four points of measurement were generated. Data of 24 students was not included in the analyses because they were absent at one or more points of measurement. The study conformed to a mixed-design with *Training Condition* as between-subjects factor and *Session* as within factor (*Limited Rotation* group, $N = 31$; $N_{female} = 20$; *Free Rotation* group, $N = 35$; $N_{female} = 23$).

4.2. Study design and procedure

The study consisted of 4 main sessions within 3 weeks. As in the pilot study, the same objects from the Shepard and Metzler (1971) mental rotation test were used. Additionally, the *Cube Comparison Test* (Ekstrom et al., 1976) was administered again after the training was finished to control for changes from before to after the trainings. The scores of the *Cube Comparison Test* ranged between −42 and + 42, but to ensure better understanding and comparability, relative values with 0 for the lowest possible score and 1.0 for the maximum score were used for the analyses. Every session contained 60 different tasks (half of them with congruent objects) based on 15 stimuli with equally distributed initial angular disparities. Before solving the tasks, the students were instructed to the corresponding kind of (either non-limited or limited) rotation tasks and rated their perceived challenge based on the instructions. To get familiar with the kinds of tasks and interaction every student solved 5 example tasks before each session. After solving a subsequent task set, students rated their mental demand and frustration (Hart & Staveland, 1988). While solving the tasks, all interactions were automatically logged and later summarized to the variables *success rates*, *net rotation time*, *time until first drag*, and *rotation way*. The study was conducted in presence but without participation of the teachers. Each of the three school classes was tested separately. To ensure the same preconditions for all three classes, we set the same time intervals between each of the training sessions in all of the classes. The study design is presented in Fig. 2 and the individual sessions were designed as follows:

- *Session 1*. Before the actual study, students were presented with the *Cube Comparison Test* (Ekstrom et al., 1976) to measure their mental

Table 2
Means and standard errors of the rotation data and single comparison tests (Bonferroni correction was set to alpha = .017).

	Free Rotation	Limited Rotation – 250%	Limited Rotation – 200%	T-tests (FR vs. LR 250%)	T-tests (FR vs. LR 200%)	T-tests (LR 200% vs. 250%)
Response time (s)	11.65 (0.94)	10.98 (0.81)	10.93 (0.78)	t(20) = 1.176, p = .254	t(20) = 0.873, p = .393	t(20) = 0.096, p = .924
Rotation way (°)	522.88 (64.60)	106.52 (11.34)	61.72 (6.67)	t(20) = 6.926, p < .001	t(20) = 7.481, p < .001	t(20) = 8.612, p < .001
Number of drags	1.42 (0.14)	1.00 (0.11)	0.75 (0.08)	t(20) = 2.790, p = .011	t(20) = 4.983, p < .001	t(20) = 5.499, p < .001
Net rotation time (s)	6.36 (0.81)	2.16 (0.32)	1.16 (0.20)	t(20) = 6.627, p < .001	t(20) = 7.689, p < .001	t(20) = 6.241, p < .001
Time until first drag (s)	0.86 (0.10)	2.84 (0.39)	3.51 (0.48)	t(20) = −5.653, p < .001	t(20) = −5.828, p < .001	t(20) = −2.100, p = .049

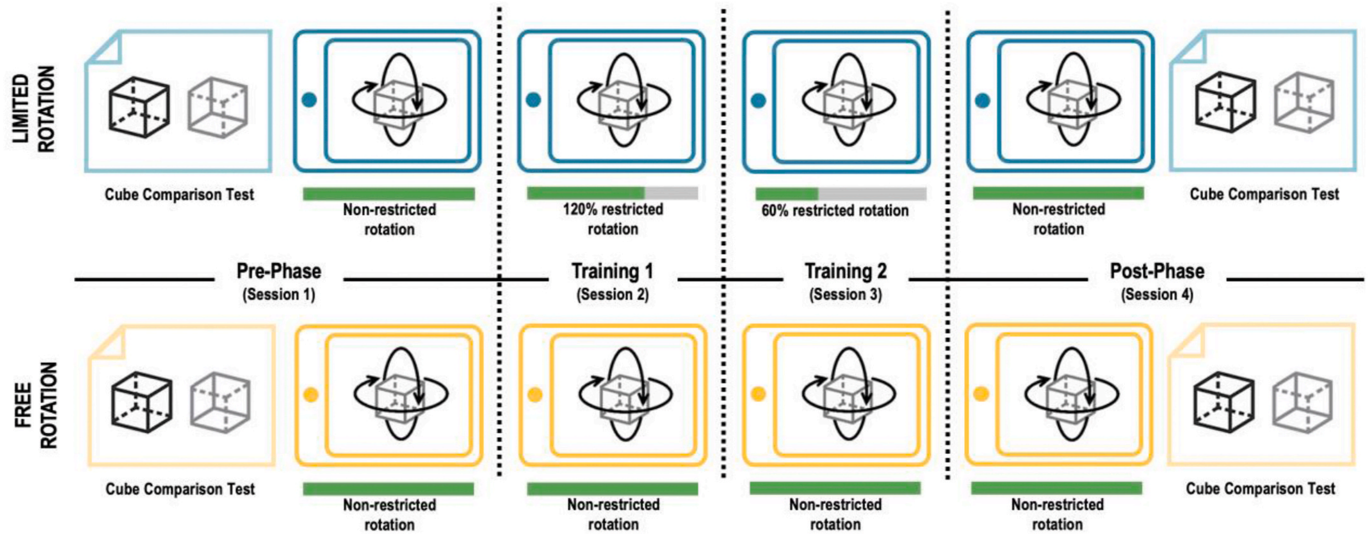

Fig. 2. Study design of the main study.

rotation performance. During Session 1, all participants solved the same set of tasks without any rotation limitations. Data from this session allowed for recording a baseline on indicators of rotation behavior independently of the *Training Condition.* Again, in this and the following sessions the students had to solve 60 tasks per session that were presented in randomized order.

- *Session 2.* To prevent pre-differences in spatial abilities students were equally allocated based on mental rotation performance and reported gender either to *Free Rotation* training or *Limited Rotation* training. The restriction was set to 120% of the initial angular disparity for the students in the *Limited Rotation* group, while students in the *Free Rotation* group were allowed to rotate without restrictions. During Session 2 and Session 3, the students were tested in two separate rooms to avoid the students knowing the differences between the experimental conditions.
- *Session 3.* This session took place directly after the previous session and all students were allocated to the same group as in Session 2, either to *Free Rotation* training or *Limited Rotation* training. The rotation restriction was set to 60% of the initial angular disparity, to initiate even more mental processes and enhance the expected learning success. At the same time students in the *Free Rotation* group were allowed to rotate without limitations again.
- *Session 4.* In the third week, all students were again presented with the same non-restricted tasks as in Session 1 but in randomized order. This procedure was chosen to allow for examining developments in rotation behavior depending on the training conditions. Additionally, after finishing the task sets and a pause of 10 min, students solved the Cube Comparison Test (Ekstrom et al., 1976) again with different tasks as in the first session to measure their mental rotation performance after the trainings.

4.3. Results

In a first step, we analyzed whether mental rotation skills were equally distributed in both groups (see section 4.3.1). In a second step, we conducted MANOVAs and checked for multivariate effects and, in case of significant results, for univariate effects to build a foundation for the following single-comparison analyses. Due to the way the different variables were recorded, we used two different MANOVAs to analyze the data regarding success rate, mental demand and frustration (measured once per participant; see section 4.3.2) as well as the rotation behavior of the participants (measured once per task; see section 4.3.3).

As in the pilot study, we used a MANOVA to explore effects of the within-group factor *Session* and the between-group factor *Training Condition* (*Free Rotation* vs. *Limited Rotation*) regarding the dependent variables *success rate*, *mental demand*, and *frustration*. For all follow-up single-comparison tests, Bonferroni correction was applied depending on the number of tests per hypothesis and alpha level was set to .006 (correction of 9 steps, while training) and 0.013 (correction of 4 steps for the before-after-comparisons).

4.3.1. Control variable: general mental rotation skills

In order to test whether the equal allocation of participants to conditions regarding spatial abilities was successful, we performed a *t*-test to compare mental rotation skills between the two groups based on the results of the *Cube Comparison Test* (Ekstrom et al., 1976) in *session 1*. Descriptive results are presented in Table 3. The *t*-test revealed no differences between both groups in session 1, $t(64) = -1.084$, $p = .283$, indicating an equal allocation of the participants regarding their spatial abilities.

4.3.2. MANOVA and univariate effects for participants' success rate, mental demand, and frustration

Table 4 presents the means and standard errors for the three dependent variables for the two experimental conditions. The MANOVA on these scores revealed significant multivariate effects for *Session*, $V = 0.530$, $F(9, 56) = 7.013$, $p < .001$, $\eta_p^2 = 0.530$, and the interaction between *Training Condition* and *Session*, $V = 0.427$, $F(9, 56) = 4.632$, $p < .001$, $\eta_p^2 = 0.427$. There was no significant main effect for the between-subjects factor *Training Condition*, $V = 0.899$, $F(3, 62) = 2.324$, $p = .084$, $\eta_p^2 = 0.101$. Univariate analyses were conducted to identify the sources (per dependent variable) of the effects for the within-factor *Session* and the interaction between *Training Condition* and *Session*.

Univariate within-subjects tests for *Session* showed significant effects for *mental demand*, $F(2.77, 177.49) = 6.484$, $p = .001$, *frustration*, $F(2.50, 159.74) = 4.282$, $p = .010$, and *success rate*, $F(2.20, 140.69) = 13.455$, $p < .001$, indicating that there are significant differences from one level to the other for the respective variables *mental demand*, *frustration* and

Table 3
Means and standard errors for the *Cube Comparison Test*.

Session	Limited Rotation		Free Rotation	
	n	*M* (*SE*)	n	*M* (*SE*)
1	31	0.499 (.03)	35	0.544 (.03)
4	31	0.667 (.02)	35	0.648 (.03)

Table 4
Means and standard errors for all dependent variables.

	Session	Limited Rotation		Free Rotation	
		N	M (SE)	N	M (SE)
Success Rate	1	31	.898 (.012)	35	.901 (.011)
	2	31	.847 (.018)	35	.915 (.011)
	3	31	.821 (.020)	35	.895 (.016)
	4	31	.939 (.013)	35	.913 (.019)
Mental Demand	1	31	10.35 (.848)	35	9.49 (.992)
	2	31	11.03 (.866)	35	10.00 (.952)
	3	31	13.39 (.902)	35	8.83 (1.013)
	4	31	9.32 (.878)	35	7.17 (1.083)
Frustration	1	31	5.19 (.982)	35	5.31 (.806)
	2	31	7.23 (.948)	35	4.94 (.697)
	3	31	8.03 (.880)	35	4.57 (.905)
	4	31	4.94 (.893)	35	3.46 (.734)

success rate. Nevertheless, the univariate test does not tell in which *Training Condition* and between which *Sessions* these differences occur. In a further step, therefore, interactions are considered in more detail, as well as later subsequent single comparisons.

The interaction between *Training Condition* and *Session* showed significant effects for *mental demand*, $F(2.77, 177.49) = 3.088$, $p = .032$, and *success rate*, $F(2.20, 140.69) = 9.783$, $p < .001$, but not for *frustration*, $F(2.50, 159.74) = 2.652$, $p = .061$. This indicates that the interaction between *Training Condition* and *Session* occurred especially in regard to the perceived *mental demand* and *success rates*, but that there were no differences from one *Session* to the next between the *Training Conditions* for *frustration*. Again, to gain knowledge about the loci of the interactions for *mental demand* and *success rate*, further analyses (single comparisons) were conducted.

Based on the above-described results and in line with the aforementioned foci, we conducted single comparison tests for the significant variables based on the univariate effects for within-comparisons and interactions. Values of the *t*-tests are presented in Table 6. MANOVA and Univariate effects for rotation behavior per task.

For the indicators of rotation behavior (see Table 5), we conducted similar analyses as for product-oriented data, to get deeper insights into the rotation processes in both *Training Conditions*.

The second MANOVA including the indicators for rotation behavior showed significant multivariate effects of the rotation data on the between-subjects factor *Training Condition*, $V = 0.581$, $F(5, 60) = 16.617$, $p < .001$, $\eta_p^2 = 0.581$, the within-subjects-factor *Session*, $V = 0.889$, $F(15, 50) = 26.698$, $p < .001$, $\eta_p^2 = 0.889$, and the interaction of *Training Condition* and *Session*, $V = 0.879$, $F(15, 50) = 24.274$, $p < .001$, $\eta_p^2 = 0.879$. These results were followed-up with univariate tests to examine the sources of the main and interaction effects considering the specific dependent variables.

Table 5
Mean and standard errors for all rotation variables.

	Session	Limited Rotation		Free Rotation	
		n	M (SE)	n	M (SE)
Response time	1	31	12.29 (.51)	35	12.22 (.57)
	2	31	11.54 (.51)	35	11.21 (.50)
	3	31	11.16 (.57)	35	10.21 (.46)
	4	31	9.66 (.33)	35	9.77 (.67)
Rotation way	1	31	510.58 (35.60)	35	490.61 (23.67)
	2	31	88.12 (3.84)	35	431.16 (22.53)
	3	31	41.00 (2.78)	35	388.31 (18.85)
	4	31	377.60 (20.40)	35	379.18 (25.77)
Number of drags	1	31	6.79 (.48)	35	6.69 (.46)
	2	31	1.45 (.08)	35	6.29 (.48)
	3	31	.89 (.07)	35	5.96 (.38)
	4	31	5.72 (.37)	35	6.18 (.60)
Net rotation time	1	31	4.18 (.24)	35	4.50 (.22)
	2	31	1.28 (.12)	35	3.48 (.22)
	3	31	.64 (.08)	35	3.01 (.19)
	4	31	2.70 (.12)	35	2.81 (.21)
Time until first drag	1	31	1.92 (.17)	35	1.97 (.11)
	2	31	3.84 (.26)	35	2.31 (.13)
	3	31	3.94 (.39)	35	2.53 (.20)
	4	31	2.26 (.18)	35	2.11 (.20)

Univariate tests for *Session* showed significant effects for *response time*, $F(2.61, 167.21) = 13.259$, $p < .001$, $\eta_p^2 = 0.172$, *rotation way*, $F(2.05, 131.325) = 107.038$, $p < .001$, $\eta_p^2 = 0.626$, *number of drags*, $F(2.49, 159.47) = 61.099$, $p < .001$, $\eta_p^2 = 0.488$, *net rotation time*, $F(2.03, 129.84) = 116.916$, $p < .001$, $\eta_p^2 = 0.646$, and *time until first drag*, $F(2.35, 150.10) = 25.175$, $p < .001$, $\eta_p^2 = 0.282$. This indicates that the respective values of the dependent variables differ significantly from one session to the next. Nevertheless, to identify the exact transformations from one session to the next, again, single comparisons were performed.

Univariate tests for *Training Condition* revealed significant effects on *rotation way*, $F(1, 64) = 55.834$, $p < .001$, $\eta_p^2 = 0.466$, *number of drags*, $F(1, 64) = 29.039$, $p < .001$, $\eta_p^2 = 0.312$, *net rotation time*, $F(1, 64) = 37.463$, $p < .001$, $\eta_p^2 = 0.369$, and *time until first drag*, $F(1, 64) = 13.208$, $p = .001$, $\eta_p^2 = 0.171$, but not for *response time*, $F(1, 64) = 0.321$, $p = .573$, $\eta_p^2 = 0.005$. Results indicate that the values of the variables differ between experimental *Training Conditions* (*Limited Rotation* vs. *Free Rotation*). Analyses of the exact sources (e.g., at which restriction levels differences occur) are reported in the single comparisons section (see Table 7).

Univariate tests for the interaction between *Training Condition* and *Session* showed significant effects for *rotation way*, $F(2.05, 131.325) = 68.112$, $p < .001$, $\eta_p^2 = 0.516$, *number of drags*, $F(2.49, 159.47) = 45.682$, $p < .001$, $\eta_p^2 = 0.416$, *net rotation time*, $F(2.03, 129.84) = 36.187$, $p < .001$, $\eta_p^2 = 0.361$, and *time until first drag*, $F(2.35, 150.10) = 10.464$, $p < .001$, $\eta_p^2 = 0.141$. There was no significant effect for *response time*, $F(2.61, 167.21) = 0.612$, $p = .608$, $\eta_p^2 = 0.009$. These results indicate that rotation behavior for the respective variables differs over the course of the *Sessions* depending on the *Training Condition*.

Based on the results from the univariate tests, we conducted single comparison tests for the significant factors. For this reason, *response time* was excluded from between comparisons in these analyses. Consequently, Hypothesis 4a has to be rejected since no between or interaction effects were revealed during the analysis. The remaining single comparison tests of indicators for rotation behavior are presented in Table 7.

5. Summary and discussion

The following analysis and interpretation of the results was conducted with two different foci:

1. *Manipulation Check.* Firstly, we checked whether the intended consequences of the rotation restrictions were realized during the actual training sessions at the 120% and 60% rotation restrictions. We were especially interested in whether *Limited Rotation* and *Free Rotation* differ in terms of *mental demand*, *success rate*, and indicators for rotation behavior during training. This was investigated by within-condition-comparisons (*session 1* vs. *session 2, session 2* vs. *session 3, session 3* vs. *session 4*). We also checked for effects between both *Training Conditions* at the respective training sessions (see section 5.1).
2. *Training effects.* Secondly, we were specifically interested in whether the *Limited Rotation* training increased the use of mental resources in a more beneficial way than the *Free Rotation* training. Variables of interest in this regard are *success rate, mental demand* and *indicators of rotation behavior (net rotation time, time until first drag, number of drags).* To test for training effects in *Limited Rotation* and *Free Rotation*, we conducted within-condition-comparisons for the non-restricted tasks from *session 1* to *session 4*. Between-comparisons of *Limited Rotation* and *Free Rotation* group at *session 4* are reported as well (see section 5.2).

Table 6
Single comparison tests for all motivational and performance variables (Bonferroni correction: alpha = .006 while training and alpha = .013 for before-after-comparisons).

	Mental Demand		Frustration		Success Rate	
Within comparisons	Limited Rotation	Free Rotation	Limited Rotation	Free Rotation	Limited Rotation	Free Rotation
Session 1 vs. 2	$t(30) = -0.817, p = .420$	$t(34) = -0.481, p = .633$	$t(30) = -1.607, p = .118$	$t(34) = 0.611, p = .545$	$t(30) = 3.595, p = .001$	$t(34) = -1.379, p = .177$
Session 2 vs. 3	$t(30) = -3.065, p = .005$	$t(34) = 1.340, p = .189$	$t(30) = -1.131, p = .267$	$t(34) = 0.486, p = .630$	$t(30) = 2.616, p = .014$	$t(34) = 2.082, p = .045$
Session 3 vs. 4	$t(30) = 4.692, p < .001$	$t(34) = 1.437, p = .160$	$t(30) = 3.821, p = .001$	$t(34) = 1.404, p = .169$	$t(30) = -8.185, p < .001$	$t(34) = -0.814, p = .421$
Session 1 vs. 4	$t(30) = 1.063, p = .296$	$t(34) = 2.723, p = .010$	$t(30) = 0.210, p = .835$	$t(34) = 1.992, p = .054$	$t(30) = -3.288, p = .003$	$t(34) = -0.648, p = .521$
Between comparisons						
Session 1	$t(64) = 0.657, p = .513$		No between nor interaction effect, as per MANOVA		$t(64) = -0.131, p = .896$	
Session 2	$t(64) = 0.795, p = .430$				$t(64) = -3.216, p = .002$	
Session 3	$t(64) = 3.324, p = .001$				$t(64) = -2.958, p = .004$	
Session 4	$t(64) = 1.518, p = .134$				$t(64) = 1.075, p = .287$	

Table 7
Single comparison tests for all rotation variables (Bonferroni correction: alpha = .006 while training and alpha = .013 for before-after-comparisons).

	Response time	Rotation way	Number of drags	Net rotation time	Time until first drag
Within comparisons – Limited Rotation group					
Session 1 vs. 2	$t(30) = 1.159, p = .256$	$t(30) = 12.355, p < .001$	$t(30) = 11.133, p < .001$	$t(30) = 11.698, p < .001$	$t(30) = -5.848, p < .001$
Session 2 vs. 3	$t(30) = 0.853, p = .400$	$t(30) = 20.274, p < .001$	$t(30) = 11.282, p < .001$	$t(30) = 8.609, p < .001$	$t(30) = -0.318, p = .753$
Session 3 vs. 4	$t(30) = 2.851, p = .008$	$t(30) = -17.225, p < .001$	$t(30) = -13.679, p < .001$	$t(30) = -16.138, p < .001$	$t(30) = 4.275, p < .001$
Session 1 vs. 4	$t(30) = 5.529, p < .001$	$t(30) = 4.388, p < .001$	$t(30) = 2.161, p = .039$	$t(30) = 6.076, p < .001$	$t(30) = -1.877, p = .070$
Within comparisons - free rotation group					
Session 1 vs. 2	$t(34) = 1.748, p = .089$	$t(34) = 2.509, p = .017$	$t(34) = 1.147, p = .260$	$t(34) = 4.427, p < .001$	$t(34) = -3.069, p = .004$
Session 2 vs. 3	$t(34) = 2.274, p = .029$	$t(34) = 2.374, p = .023$	$t(34) = 0.910, p = .369$	$t(34) = 3.602, p = .001$	$t(34) = -1.214, p = .233$
Session 3 vs. 4	$t(34) = 0.705, p = .486$	$t(34) = 0.376, p = .709$	$t(34) = -0.449, p = .656$	$t(34) = 1.063, p = .295$	$t(34) = 2.225, p = .033$
Session 1 vs. 4	$t(34) = 3.264, p = .003$	$t(34) = 4.531, p < .001$	$t(34) = 1.126, p = .268$	$t(34) = 7.198, p < .001$	$t(34) = -0.749, p = .459$
Between comparisons					
Session 1	No between nor interaction effects, as per MANOVA	$t(64) = 0.477, p = .635$	$t(64) = 0.149, p = .882$	$t(64) = -0.994, p = .324$	$t(52.058) = -0.233, p = .817$
Session 2		$t(35.97) = -15.008, p < .001$	$t(35.84) = -9.938, p < .001$	$t(51.53) = -8.737, p < .001$	$t(43.65) = 5.220, p < .001$
Session 3		$t(35.47) = -18.233, p < .001$	$t(35.97) = -13.007, p < .001$	$t(45.12) = -11.361, p < .001$	$t(45.55) = 3.242, p = .002$
Session 4		$t(64) = -0.047, p = .963$	$t(64) = -0.629, p = .532$	$t(52.014) = -0.418, p = .678$	$t(64) = 0.560, p = .578$

5.1. Manipulation Check

As shown in Table 6, no differences between the *Limited Rotation* and *Free Rotation* training were revealed for *success rate* during *session 1*, which indicates that all students had the same learning prerequisites regarding their spatial abilities. Over the course of the sessions, the *Free Rotation* group remained at the same *success rate* level while at the same time, *success rates* in the *Limited Rotation* group decreased significantly with higher rotation restrictions and increased significantly from *session 3* to *session 4*, when free rotation is finally allowed again. Moreover, success rates in both *Training Conditions* differ in *session 2* and *session 3*, which is the source of the interaction effect between *Training Condition* and *Session* for the dependent variable *success rate*. All in all, results on *success rate* indicate that solving tasks in the *Limited Rotation* training is of higher difficulty and causes higher task demands compared to the *Free Rotation* training. This result is also supported by values of the within-comparisons for *mental demand* and *frustration*: *Mental demand* exhibits no change in the *Limited Rotation* group from *session 1* to *session 2*, but an increment from *session 2* to *session 3*, and again a drop from *session 3* to *session 4,* while no changes occur in the *Free Rotation* group. Furthermore, such difference in perceived *mental demands* is reflected in the significant difference between *Limited Rotation* and *Free Rotation* training in *session 3* with higher reported *mental demand* in the *Limited Rotation* group. This can be seen as the source of the interaction between *Training Condition* and *Session* for the dependent variable *mental demand.* Complementary, within-comparisons for *frustration* revealed no changes over the course of the *Free Rotation* training, while the *Limited Rotation* group reveals a significant change from *session 3* to *session 4*, indicating that frustration differs to a substantial amount between the hardest restriction and the free rotation options in *session 4*. Fig. 3 provides an overview of normalized means for *success rate, mental demand, and frustration* over all four sessions.

Regarding the participants' rotation behavior, *Rotation way* in the *Limited Rotation* group shows a significant decrement from *session 1* to *session 2*, and again from *session 2* to *session 3*. This is followed by an increment from *session 3* to *session 4*, while at the same time no such changes occur in the *Free Rotation* group. This indicates that, due to the limitations forced by the rotation restrictions, students in the *Limited Rotation* group used less way to rotate during training, but increased the rotation way significantly when rotation is allowed again in *session 4*. Also, comparisons between *Limited Rotation* and *Free Rotation* in *session 2* and *session 3* differ significantly with lower values in the *Limited Rotation* group, these effects disappear when all students are allowed for free rotation in *session 4* again.

A similar pattern was revealed for *number of drags* and *time until first*

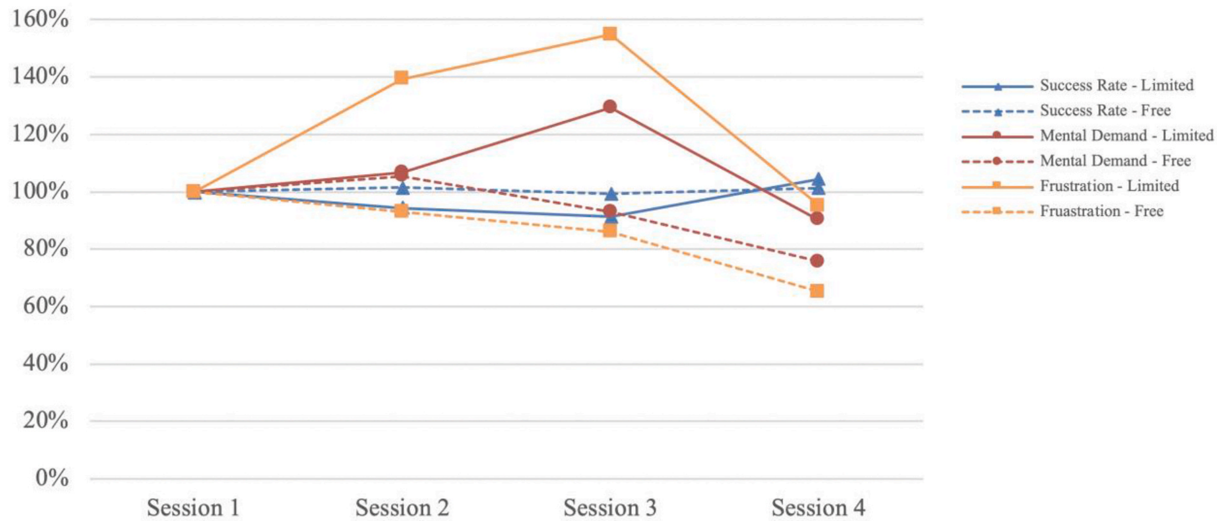

Fig. 3. Normalized means reflecting the learners' decrease and increase in *success rate*, *mental demand*, and *frustration* for *Limited* and *Free Rotation* group over all four sessions.

drag, with significant changes from *session 1* to *session 2:* While *number of drags* decreases, the *time until first drag* increases with a higher *rotation restriction.* A similar and also significant pattern regarding *time until first drag* occurs in the *Free Rotation* group. However, the increment in the *Limited Rotation* group from *session 1* to *session 2* is 100.0% while the corresponding values in the *Free Rotation* group is only 17.3% higher compared to *session 1*. Also, changes occur from *session 2* to *session 3* for *number of drags,* which is even further decreased in *session 3* compared to *session 2*. Data on rotations show a relaxing effect from *session 3* to *session 4* in the *Limited Rotation* group with increasing *number of drags* and a decreasing *time until first drag.* Again, no such effects are observed in the *Free Rotation* group. Again, between-comparisons reveal differences between the *Training Conditions* only restricted to *session 2* and *session 3*, and those mark the source of the interaction effects. Fig. 4 shows normalized means for the learners' rotation behavior over all four sessions.

To sum up, the application of rotation restrictions seems to show the intended consequences: Results on *success rates, mental demand, frustration* show a pattern that indicates that students were indeed activated to use mental resources while solving the tasks (*activation effect*) while the similarities in success rates and mental demands in the *Free Rotation* group indicate the assumed *facilitation effect*. Furthermore, results on rotation behavior suggest that students in the *Limited Rotation* condition engage for longer times in mental rotation processes before starting physical interactions (e.g. increased *time until first drag* while training sessions) and during the actual rotations (e.g. decreased *number of drags* and *rotation way*). Nevertheless, as success rates between training conditions for *session 2* and *session 3* revealed this active mental rotation occurs at the cost of performance during the training. A relevant question therefore is whether these costs can be compensated after the actual training during the last *session 4.* We report on this issue next by considering the post-training effects.

5.2. Training effects

It is of specific interest in this study whether the instructional techniques – *Free Rotation* as a facilitating tool and *Limited Rotation* as an activating tool – differ in their training effects when looking at success rates, mental demand, and frustration. In Table 6, the respective values of the within-subject comparisons from *session 1* to *session 4* are

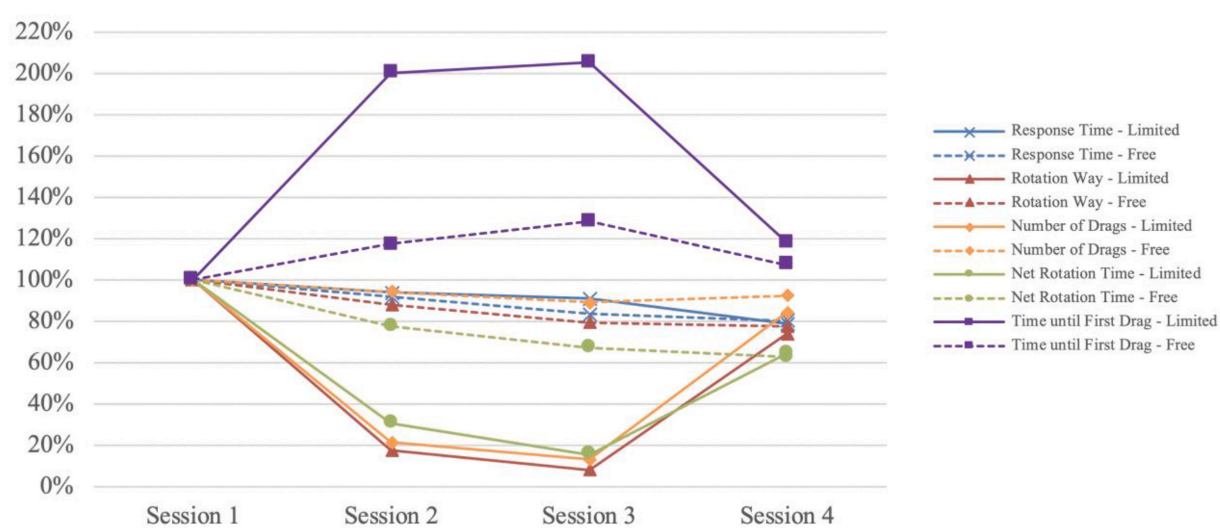

Fig. 4. Normalized means reflecting the learners' decrease and increase in different aspects of their rotation behavior for *Limited* and *Free Rotation* group over all four sessions.

presented separated by *Training Condition*.

Hypotheses 2 and 3.

Data show that *mental demand* and *frustration* are not affected in the pre-post comparison in different ways after *Limited Rotation* and *Free Rotation* training. This indicates that the significant interactions in the univariate tests should be traced back to the presented differences while training, but not to sustainable effects considering these variables after training. Based on this, Hypotheses 2 and 3 have to be rejected.

Hypothesis 1a.

This is contrasted by findings for *success rate*: Comparisons of *success rate* from *session 1* to *session 4* reveal a significant increment in the *Limited Rotation* group, while similar success rates and no significant increase from *session 1* to *session 4* are observed in the *Free Rotation* group. This indicates a beneficial training effect of the rotation restrictions for success rate. All in all, this can be interpreted as first empirical evidence for the hypothesis that the *Limited Rotation* training activates mental processes of rotation more likely than the facilitating *Free Rotation* training, which supports Hypothesis 1a.

Hypothesis 1 b.

As an additional indicator for a *post-training* effect, we considered the results of the *Cube Comparison Test* before and after the training phase. Results of a mixed 2 x 2 ANOVA with the factors *Training Condition* (*Limited Rotation* vs. *Free Rotation*) and *Session* (*session 1* vs. *session 4*) show a significant univariate within-effect for *Session*, $F(1, 64) = 50.783$, $p < .001$, but neither a significant effect of the between-factor *Training Condition*, $F(1, 64) = 0.709$, $p = .709$, nor an interaction between *Training Condition* and *Session*, $F(1, 64) = 2.728$, $p = .103$. Correspondingly, single comparison tests reveal a significant increase of the test results in both *Free Rotation*, $t(34) = -3.953$, $p < .001$, and *Limited Rotation*, $t(30) = -6.099$, $p < .001$. At this, students of both groups benefited to an equal extent in the mental rotation skills measured by the *Cube Comparison Test*, wherefore Hypothesis 1 b has to be rejected.

Hypotheses 4a – 4e.

Depending on the results of the MANOVA, hypothesis 4a, stating that students show less *time spent per task* after *Limited Rotation* training compared to *Free Rotation* training, must also be rejected (see section 4.3.3). Based on the single-comparison analyses of rotation behavior, *number of drags* and *time until first drag* revealed no significant effects that would allow for conclusions on specific training effects regarding rotation behavior from *session 1* to *session 4*, which does not support Hypotheses 4c and 4e. In contrast, *rotation way* and *net rotation time* decreased from *session 1* to *session 4* independently of the *Training Condition*, indicating that both trainings caused beneficial effects in regard to the interactions necessary for learners to solve the tasks. These rotation data after training do not allow to conclude on a specifically trained rotation behavior by the activation of rotation restrictions, therefore Hypotheses 4 b and 4 d have to be rejected. Nonetheless, both trainings lead to more efficient solving of the tasks as indicated by less *net rotation time* and *rotation way* needed in *session 4* compared to *session 1*.

In summary, these results indicate that the *Free Rotation* training is not completely based on a facilitating effect, but rather on an increment in efficiency (same *success rate* is reached with less *net rotation time* and *rotation way*) from before to after the training. In the *Limited Rotation* group, *rotation way* and *net rotation time* decreased from *session 1* to *session 4*, but these findings are accompanied by an additional increment in *success rate*. Data analyses showed a training effect and therewith an activating effect initiated by rotation restrictions in the *Limited Rotation* group. This is speaking in favor of a more activating effect with higher efficiency while solving tasks in *session 4* compared to the *Free Rotation* training. Results collectively support the *activation hypothesis* for the *Limited Rotation* group. The *Free Rotation* group showed activating effects, as well, but with lower resulting performance and efficiency increments then after the *Limited Rotation* training.

6. Conclusion

The goal of this study was to explore effects of a mental rotation training that varies the amount of limitations of the touch-based interactive rotations while solving spatial tasks on mobile devices. The specific interest of the presented investigations resulted from a range of studies on the effectiveness of interactive dynamic representations in solving mental rotation tasks (Boucheix & Chevret, 2014; Ha & Fang, 2018; Wiedenbauer & Jansen-Osmann, 2008). Most of those studies either compared external interactive dynamic rotations (e.g., physical rotation) and internal mental rotations based on statically represented tasks. Further studies investigated if and how static and interactive dynamic training translates to skills while solving dynamic and static rotation skills. Nevertheless, all existing studies miss a variation of the interactive dynamic support while rotating, so we conducted a study that amplified the typical dynamic vs. static design by the integration of a new instructional format. This was based on the ideas, that dynamic representations alone can interfere the learning process by facilitating mental processes. Also, process data that allow to track the ways of solving were not used to deeper analyze the effectiveness of the representations and trainings. This research gap was addressed with the present studies in order to amplify our knowledge about effective digital trainings on mental rotation skills.

In order to realize variations of interactive dynamic support while task solving, a tablet-based training was developed that allows for limiting the possible rotations of 3D-objects. Such a *Limited rotation training* with two kinds of limitations varying in strictness was compared against a training with an unlimited *Free rotation* mode.

Results on the students' performance and motivation showed different results based on the focus of data analysis: from before to after the training or during training. Examining the effects of the enabled rotation restrictions (see Table 4) during training data revealed a significant increase in *frustration* for the *Limited Rotation* while no changes occur while *Free Rotation* training. A similar pattern can be observed for *mental demand*: Whilst no differences could be observed during the *Free Rotation* training compared to the first session, *mental demand* raised significantly from *session 2* to *session 3* during the *Limited Rotation* training. Additionally, the success rate decreased with enabled *Limited Rotation* during session 2 and 3 and stayed at the same level for *Free Rotation* training. These results indicate a higher task difficulty, and therefore higher "costs" of using the *Limited Rotation* condition regarding *mental demand*, *frustration* and *success rate* compared to the results of *Free Rotation* condition which remained on a comparable low level over the course of the training. Focusing on the post-training effects from the first to the last session, no changes for perceived *mental demand* and *frustration*, but differences regarding the *success rates* after the training sessions were observed between the training groups. While students with *Free Rotation* training showed no statistically relevant gain regarding their performance ($mean_{Session\ 1} = 0.901$, $mean_{Session\ 4} = 0.931$), students with *Limited Rotation* training could raise their performance level significantly ($mean_{Session\ 1} = 0.898$, $mean_{Session\ 4} = 0.939$). As the training in session 1 and 4 consisted of free rotatable tasks for both training groups, one can argue that it is a positive result, that the level of mental demand and frustration does not differ from before to after training although, during training differences regarding mental demand and perceived emotions occur.

For a closer look at the student's rotation behavior, data were analyzed in order to understand on which processes the positive results regarding training success in the limited rotation group are based on. Results on the students' rotation behavior showed a similar pattern based on the focus of data analyses. During the training sessions, *rotation way*, *net rotation time*, and *number of drags* are directly influenced by rotation limitations. All of these three variables are decreasing during the *Limited Rotation* training (see Table 5), which can be seen as a direct result of the limitation of rotation way. Again, no changes over the course of the training were observed for *Free Rotation* training. Time until first drag was a central variable and of specific interest, as it was seen as a direct indicator for the expected triggered mental processes while task solving in the *Limited Rotation* condition. During the training *time until first drag* was increased in the *Limited Rotation* group but remained on a similar level in the *Free Rotation* group. However, after training, t*ime until first drag* was not influenced by the *Limited Rotation* training. This result is surprising, especially when looking at the increment in success rate from before to after training in the *Limited Rotation* group. It was expected that students in this group learn over the course of the training to combine internal mental and external rotation processes to solve the task more efficiently. And the *time spent until first drag* would be an indicator for this. One reason here can be, that students indeed learn to rotate better in mind, but at the time they are allowed to use free rotation again, they would stop using mental resources in the same way as under the limitations.

Moreover, data from both groups decreased homogenously from before to after the training for *response time*, *rotation way*, and *net rotation time*. In contrast, *number of drags* and *time until first drag* showed no changes at all in both groups before and after the training. This can be seen as a hint, that both training conditions train and that maybe the effect of the limitations is not pronounced enough to translate to the variable *time until first drag*. In sum, results indicate that using a limiting tool while solving spatial tasks leads to a more activating effect for the students then solving spatial tasks without any restrictions. However, it is not completely clear how this effect can be explained on the basis of the process data.

7. Practical implications

From a practical perspective, results emphasize the importance of considering over-facilitating effects. For comparable trainings of spatial abilities, especially when using digital devices to support learning, it should be taken into account that, despite the associated facilitation of learning, mental processes should not be completely supplanted. Our results show that this requirement can be implemented by the presented instructional design technique.

This ensures that not only the learning process itself is supported, but the training also leads to long-term improvements in spatial skills. By gradually reducing the rotation limitations, a fading-out effect is achieved (Renkl, Atkinson, & Maier, 2000) which might prevent an *Illusion of Understanding* (Paik & Schraw, 2013). The rotation limitation used in the present study is a very simple method of fostering mental processes and promoting the learning process. In addition, other advantages of digital devices can be used to enable better learning, such as linking the learning process with incentives, using further gamification elements or adapting the given support for different types of learners. The knowledge gained from this can lead to individual training, that can be used in the learners' leisure time, e.g. as a game app, but also in school and higher education, where the learning path can be individually adjusted by changing the settings of the application or even adaptive learning environments.

8. Limitations and further research

One aim of future studies should address the adaptivity of training methods. It can be expected that the limitation technique is not appropriate for all learners as frustration can result especially for those who prefer cooperative over competitive learning environments. To be able to answer such complex questions regarding appropriate adaptations for different target groups, further research is required. Learner prerequisites were not considered when examining the effectiveness of the training conditions in the present study. Especially the pre-existing spatial abilities, gender or motivational variables might have been influential for the functioning of each of the training designs. High spatial abilities before training for example can reduce training effects as learners with higher abilities can compensate for disadvantages of training designs (see *Expertise Reversal Effect*; Kalyuga, 2014; Kalyuga, Ayres, Chandler, & Sweller, 2003). Furthermore, not only a *Limited Rotation* training can be beneficial for improving mental rotation skills, also the *Free Rotation* training can be useful for specific learner characteristics, especially in dependence of pre-existing motivations like anxiety of failure, interest or achievement motivation. Therefore, future studies should also focus on exploring different support and training strategies for high and low spatial ability learners based on their learner prerequisites, like their achievement motivation, math anxiety or gender identification. Because of the results from our earlier studies about gender differences in spatial abilities, we analyzed the data additionally for gender differences and found first indications, that the differences found in this study are partly based on the girls' results, and that especially boys compensate for the training characteristics. In order to replicate and further examine these indications, future research should aim at using a larger sample size. By this, additional learner prerequisites as well as different ages and nationalities can also be considered. Analyses should also be done by using more complex analysis models (e.g. path models) that display the relationship between variables such as performance, motivation, learner prerequisites, and also rotation behavior. Moreover, a longer training period with even higher rotation limitations and another test for spatial abilities several weeks after the last session should be considered to examine the long-term effects of rotation training. Although challenging, one possibility to analyze the specific processes of direct, touch based interaction could be the use of eye-tracking or measuring the pressure on the surface of the actual device while manipulating objects. Also, it has to be critically reflected, that the tasks of the MRT applied in the present study might have resulted too easy for the specific age group. The actual tasks demanded a comparison of two objects (instead of 1:4, see Vandenberg & Kuse, 1978) which were presented side by side. All in all, results show that rotation limitations can work as a tool for developing adaptive training, in which restrictions are changed based on the learner's performance.

To the best of our knowledge, this study was the first to analyze the process of solving rotation tasks under the influence of rotation limitation and the impacts on training spatial abilities. We also combined our research interest with additional cognitive as well as motivational measures during the training process and also used the data recorded by our app to examine the rotation behavior of the students with regard to training effects.

Author contribution

Michael Montag, Conceptualization, Formal analysis, Investigation, Writing – original draft, Resources, Methodology, Visualization, Project administration. Sven Bertel, Resources, Methodology, Writing – review & editing. Bjorn B de Koning, Methodology, Writing – review & editing. Steffi Zander, Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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References

Abrams, R. A., Davoli, C. C., Du, F., Knapp, W. H., & Paull, D. (2008). Altered vision near the hands. *Cognition, 107*(3), 1035–1047. https://doi.org/10.1016/j.cognition.2007.09.006

Adams, D. M., Stull, A. T., & Hegarty, M. (2014). Effects of mental and manual rotation training on mental and manual rotation performance. *Spatial Cognition and Computation, 14*(3), 169–198. https://doi.org/10.1080/13875868.2014.913050

Björk, S., & Holopainen, J. (2005). *Patterns in game design*. Boston, MA: Charles River Media.

Blohm, I., & Leimeister, J. M. (2013). Gamification: Design of IT-based enhancing services for motivational support and behavioral change. *Business and Information Systems Engineering, 5*(4), 275–278. https://doi.org/10.1007/s12599-013-0273-5

Boucheix, J. M., & Chevret, M. (2014). Alternative strategies in processing 3D objects diagrams: Static, animated and interactive presentation of a mental rotation test in an eye movements cued retrospective study. In T. Dwyer, H. Purchase, & A. Delaney (Eds.), *Diagrammatic representation and inference. Diagrams 2014. Lecture notes in computer science* (Vol. 8578, pp. 138–145). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-662-44043-8_17.

Colangelo, N., Assouline, S. G., & Gross, M. U. M. (2004). In *A nation deceived: How schools hold back America's brightest students, ume 2*. Connie Belin & Jacqueline N. Blank International Center for Gifted Education and Talent Development (NJ1).

Cosman, J. D., & Vecera, S. P. (2010). Attention affects visual perceptual processing near the hand. *Psychological Science, 21*(9), 1254–1258. https://doi.org/10.1177/0956797610380697

DeSutter, D., & Stieff, M. (2017). Teaching students to think spatially through embodied actions: Design principles for learning environments in science, technology, engineering, and mathematics. *Cognitive Research: Principles and Implications, 2*(22). https://doi.org/10.1186/s41235-016-0039-y

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests*. Princeton, NJ: Educational testing service.

Gardony, A. L., Taylor, H. A., & Brunyé, T. T. (2014a). What does physical rotation reveal about mental rotation? *Psychological Science, 25*(2), 605–612.

Ha, O., & Fang, N. (2018). Interactive virtual and physical manipulatives for improving students' spatial skills. *Journal of Educational Computing Research, 55*(8), 1088–1110. https://doi.org/10.1177/0735633117697730

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbache, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest, 8*(1), 1–51. https://doi.org/10.1111/j.1529-1006.2007.00032.x

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (task load index): Results of empirical and theoretical research. *Advances in Psychology, 52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Höffler, T. N. (2010). Spatial ability: Its influence on learning with visualizations-a meta-analytic review. *Educational Psychology Review, 22*(3), 245–269. https://doi.org/10.1007/s10648-010-9126-7

Höffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction, 17*(6), 722–738.

Hoyek, N., Collet, C., Fargier, P., & Guillot, A. (2012). The use of the Vandenberg and Kuse mental rotation test in children. *Journal of Individual Differences, 33*(1), 62–67. https://doi.org/10.1027/1614-0001/a000063

Hu, F. T., Ginns, P., & Bobis, J. (2015). Getting the point: Tracing worked examples enhances learning. *Learning and Instruction, 35*, 85–93. https://doi.org/10.1016/j.learninstruc.2014.10.002

Kalyuga, S. (2014). The Expertise reversal principle in multimedia learning. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 576–597). New York, NY, US: Cambridge University Press.

Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The Expertise reversal effect. *Educational Psychologist, 38*(1), 23–31. https://doi.org/10.1207/S15326985EP3801_4. Retrieved from.

Keehner, M., Hegarty, M., Cohen, C., Khooshabeh, P., & Montello, D. (2008). Spatial reasoning with external visualizations: What matters is what you see, not whether you interact. *Cognitive Science, 32*(7), 1099–1132. https://doi.org/10.1080/03640210801898177

Koch, M., Ott, F., & Oertelt, S. (2013). *"Gamification von business software - Steigerung von Motivation und partizipation". Schriften zur soziotechnischen integration, band 3. Schriften zur soziotechnischen integration, band 3. München: Forschungsgruppe kooperationssysteme, Universität der Bundeswehr München*. https://doi.org/2194-0282.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*(6), 1479–1498. https://doi.org/10.2307/1130467

Lowe, R. K., & Schnotz, W. (2014). *Animation principles in multimedia learning. The cambridge handbook of multimedia learning* (2nd ed.). https://doi.org/10.1017/CBO9781139547369.026

Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the purdue spatial visualization tests: Visualization of rotations (PSVT:R). *Educational Psychology Review, 25*(1), 69–94. https://doi.org/10.1007/s10648-012-9215-x

Münzer, S., Seufert, T., & Brünken, R. (2009). Learning from multimedia presentations: Facilitation function of animations and spatial abilities. *Learning and Individual Differences, 19*(4), 481–485. https://doi.org/10.1016/j.lindif.2009.05.001

Newcombe, N. S. (2010). Picture this. Increasing math and science learning improving spatial thinking. *American Educator, 34*, 29–43. https://doi.org/10.1037/A0016127

Paik, E. S., & Schraw, G. (2013). Supplemental material for learning with animation and illusions of understanding. *Journal of Educational Psychology, 105*(2), 278–289. https://doi.org/10.1037/a0030281.supp

Peters, M., & Battista, C. (2008). Applications of mental rotation figures of the shepard and metzler type and description of a mental rotation stimulus library. *Brain and Cognition, 66*, 260–264. https://doi.org/10.1016/j.bandc.2007.09.003

Pietsch, S., & Jansen, P. (2012). Different mental rotation performance in students of music, sport and education. *Learning and Individual Differences, 22*(1), 159–163. https://doi.org/10.1016/j.lindif.2011.11.012

Reed, C. L., Grubb, J. D., & Steele, C. (2006). Hands up: Attentional priorization of space near the hand. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 166–177. https://doi.org/10.1037/0096-1523.32.1.166

Reilly, D., Neumann, D. L., & Andrews, G. (2017). Gender differences in spatial ability: Implications for STEM education and approaches to reducing the gender gap for parents and educators. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education* (pp. 195–224). Cham: Springer.

Renkl, A., Atkinson, R. K., & Maier, U. (2000). *From studying examples to solving problems: Fading worked-out solution steps helps learning.of the 22nd Annual Conference of the* (pp. 393–398). https://doi.org/10.1.1.23.6816.

Rodán, A., Contreras, M. J., Rosa Elosúa, M., & Gimeno, P. (2016). Experimental but not sex differences of a mental rotation training program on adolescents. *Frontiers in Psychology, 7*, 1050. https://doi.org/10.3389/fpsyg.2016.01050

Salomon, G. (1994). *Interaction of media, cognition and learning*. Hillsdale: Lawrence Erlbaum Associates.

Scheiter, K. (2014). The learner control principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 487–512). New York, NY, US: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.025.

Schnotz, W., & Rasch, T. (2005). Enabling, facilitating, and inhibiting effects of animations in multimedia learning: Why reduction of cognitive load can have negative results on learning. *Educational Technology Research & Development, 53*(3), 47–58. https://doi.org/10.1007/BF02504797

Schwan, S., & Riempp, R. (2004). The cognitive benefits of interactive videos: Learning to tie nautical knots. *Learning and Instruction, 14*(3), 293–305. https://doi.org/10.1016/j.learninstruc.2004.06.005

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York, NY, US: Springer.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education. When, why, and how?. In *Psychology of learning and motivation - advances in research and theory* (Vol. 57)Elsevier Inc. https://doi.org/10.1016/B978-0-12-394293-7.00004-2.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402. https://doi.org/10.1037/a0028446

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 Years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817–835. https://doi.org/10.1037/a0016127

Zander, S., Wetzel, S., & Bertel, S. (2016). Rotate it! - Effects of touch-based gestures on elementary school students'solving of mental rotation tasks. *Computers and Education, 103*, 158–169. https://doi.org/10.1016/j.compedu.2016.10.007

Wiedenbauer, G., & Jansen-Osmann, P. (2008). Manual training of mental rotation in children. *Learning and Instruction, 18*(1), 30–41. https://doi.org/10.1016/j.learninstruc.2006.09.009

Bertel, S., Wetzel, S., & Zander, S. (2017). Physical Touch-Based Rotation Processes of Primary School Students. *Spatial Cognition X*. Springer LNAI.