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RESEARCH ARTICLE

Spatial task solving on tablets: analysing mental and physical rotation processes of 12–13-year olds

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Abstract

Spatial skill assessment and training are promising fields of application for tablets, as touch-based interaction can prime and support mental transformations of spatial knowledge. We report on a study with 49 secondary school students who used our iPad app to solve mental and physical rotation tasks. During physical rotation, students were able to rotate 3D stimuli using touch interaction. Results show specific similarities (e.g., regarding angular disparity effects) as well as differences between mental and physical conditions, such as for task success, mental effort, efficiency; all to the advantage of the physical condition. 12–13-year olds can benefit from these advantages without previous task training, whereas previous research showed this to be different for younger students. In a second step, our analysis compares low and high achievers regarding physical rotation behaviour and motivational variables, including expected success. The results lay grounds for constructing individualized, tablet-based training apps for spatial skills.

Keywords Spatial skill assessment · Mental and physical rotation · Differences in physical rotation behaviour · Secondary school students

Introduction

Over the last years, the use of interactive media devices in schools has become more and more important. Computers, smart boards, and tablet computers offer new opportunities for interactive lessons that can verifiably improve students' motivation and learning outcomes (e.g. Clarke and Svanaes 2013; Ifenthaler and Schweinbenz 2013). Spatial skill training seems to be an especially promising field of application for tablets. One reason is that physical interaction via touch gestures can be used to prime and support mental transformations of spatial knowledge (Chu and Kita 2011; Goldin-Meadow et al. 2012). Compared

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to verbal or mathematical skills, spatial skill training is still underrepresented in school curricula (Colangelo et al. 2004). This is surprising as good spatial skills have been shown to be important for success in many domains, including Science, technology, engineering, and mathematics (STEM; Wai et al. 2009). A second crucial property of using tablets for interactive lessons is that they are often used on an individual basis, one tablet per student. For spatial problem solving, this permits recording students' individual solution strategies, examining inter-individual procedural differences, as well as, possibly, closely adapting future training programs to individual prerequisites.

So far, there is little research investigating and comparing mental (static) and physical (dynamic) rotation processes using interactive technologies, such as tablets. Therefore, our focus lies on how touch-based interactions are utilized to respectively facilitate mental and physical rotation processes. In particular, we compare spatial task performance, mental effort and motivation between a purely mental, static version (mental rotation) of an iPad app and an interactive version (physical rotation) which afforded touch input to manipulate the orientation of 3D objects. Regarding study design and data analysis, we significantly extend the approach of Zander et al. (2016) who explored how students in 3rd grade benefit from being able to physically interact with an iPad when solving spatial tasks. This was especially done by considering different rotation strategies of highly and lowly successful solution processes during data analysis. Secondly, as the data by Zander et al. (2016) points to a familiarization need for physical rotation for 3rd graders (likely due to the developmental stage regarding 3D mental rotation), we decided to recruit from an older age group (12–13 years old). With these two perspectives combined, we take a novel, process-based view on the problem-solving processes that occur during physical rotation to get a deeper understanding of interaction processes of students. We examine in detail how students interacted with the app over the course of physical rotation tasks. Our approach compares problem-solving behaviour on the basis of log file data from touch-interaction of students at both ends of the performance range (low vs. high success), thereby complementing the approach of Bertel et al. (2017), who analysed students' general rotation behaviour and strategies.

The following section gives an overview about the relevant existing research on mental and physical rotation abilities, and on their development and training. In the third section, we present aims, research questions, and hypotheses established for our study. The fourth section describes our iPad app as well as the study design. Next are the results of our study, including a detailed analysis of students' physical rotation processes. Finally, in the sixth section, we discuss and reflect upon our study design, results, draw general conclusions, and outline future work.

Models and theories on mental rotation

Over the years, several models and theories about spatial abilities and their relationship with other (largely, cognitive) abilities were developed. Most of these list *mental rotation* as one factor among others, such as mental folding or spatial visualization (e.g., Gardner 1983; Smith 1964; Reilly et al. 2017). Mental rotation describes the ability to mentally rotate two- or three-dimensional objects through a sequence of spatial information transformations.

Shepard and Metzler (1971) were the first to study mental rotation using three-dimensional cube figures. They placed two cube figures side by side and had participants decide if those figures were the same or different (e.g., mirrored) figures. For same figures, the time to solve the task was found to increase linearly with increasing angular disparity between the figures (angular disparity effect, ADE). Over the years, a variety of mental rotation models were developed (e.g., Bethell-Fox and Shepard 1988; Funt 1983; Hamrick and Griffiths 2014; Just and Carpenter 1985; Xue et al. 2017). Just and Carpenter (1976) identified three functional phases during mental rotation: (1) a search phase, (2) a transformation and comparison phase, and (3) a confirmation phase (Fig. 1). The process starts with (1), where likely matching segments of the figures are identified based on simple heuristics. This is followed by (2), in which one of these segments is mentally rotated in steps of approximately 50° until an angular disparity of less than 25° between the segments is achieved. In (3), the final decision if figures are the same or different can either be made or not. If it cannot, the whole process starts over until a decision can finally be made. While other models of mental rotation differ in details of description, most of them consist of similar sub-processes as those postulated by Just and Carpenter.

Training and support of mental rotation through physical interaction

The ability to reliably perform mental rotations develops as one gets older. Roberts and Bell (2002) compared the two- and three-dimensional mental rotation performance of 8-year-olds and college students. The adult group showed significantly higher performance than the children group. Depending on the task type, men outperformed women and boys outperformed girls. The latter findings are in line with studies that had previously discovered stable sex differences across all age groups to the benefit of males (see Reilly et al. (2017) for an overview).

Mental rotation skills can be improved by training (e.g., Adams et al. 2014; Wiedenbauer and Jansen-Osmann 2008), also when training is realized by an option to physically rotate either objects themselves or their dynamic rotatable visualizations. It can be assumed that processes during pure mental rotation are driven by limited resources of working memory and therefore induce mental load (Just and Carpenter 1976). It is especially for those learners with low spatial abilities that keeping mental load low may enable the necessary processes for task success (Sweller et al. 1998, 2011). One way to do so is through offloading information and mental transformations onto perceptual-motor processes (Ballard et al. 1997; Kirsh and Maglio 1994; Wilson 2002; Zhang and Norman 1994; Choi et al. 2014). Chu and Kita (2011) report on a study in which university students were encouraged to produce gestures during mental rotation tasks (e.g., representational gestures like grasping). They found that the success rate of participants using gestures was higher compared to a control group where gestures were prohibited. Chu and Kita argue that the offloading

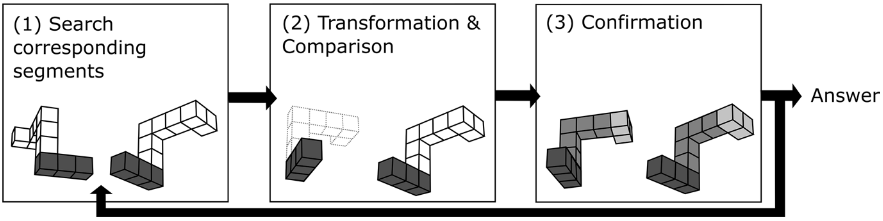

Fig. 1 An illustration of the functional phases during mental rotation according to Just and Carpenter (1976)

of necessary intermediate transformations during mental rotation to gestures was especially beneficial for participants who had difficulties solving the tasks.

Mental rotation training via manual rotation of external representations can be realized by using interactive technologies. Regarding the relationship between mental rotation and physical interaction, Adams et al. (2014) showed that training physical rotation of proxy objects via the use of a rubber ball containing a 3-degrees-of-freedom inertia sensor improves mental rotation performance. For 3rd graders working with Shepard and Metzler cube figures on tablets either with physical interaction or in a mental version without interaction, Zander et al. (2016) found evidence that such young students required familiarization through mental rotation in order to be able to make full use of the interactive potential during physical rotation tasks. With such familiarization, it was assumed that intermediate representations were offloaded to the tablet providing a direct visual feedback of the transformations. In particular, mental effort was lower and task success was higher during physical rotation when it had been preceded by (static) mental rotation training than when students had received no such familiarization.

All in all, research on support of mental rotation via gesture-based interaction with technical devices is promising. The underlying processes of beneficial effects are seen in an effective offloading of complex mental processes to external representations.

A comparison of physical and mental rotation processes

Gardony et al. (2014) compared processes when solving mental rotation tasks with processes during physical rotation controlled through a ball held in hand. They found a number of similarities between the conditions, including similar linear relationships between response time and initial angular disparity (ADE, as discussed above). Also, for successful tasks, participants mostly rotated the figures until a canonical, low angular disparity of 30°–60° was achieved. This range is comparable to the 50° mark postulated by Just and Carpenter (1976) as the final angular offset for mental rotation tasks. Crucially, such similarities seem not to be tied to a particular mode of physical input: Using an Arcball metaphor and touch inputs on iPads, Bertel et al. (2017) found similar trajectories of angular disparity over time as Gardony et al. (2014). This finding is important as it points to general similarities of the cognitive processes respectively involved in physical and mental rotation and as it does not point to explanations that the found procedural similarities would simply be caused by properties of specific input modes for physical interaction.

The processes described by Just and Carpenter (1976) for mental rotation are based on the assumption that only segments of the 3D figures are mentally transformed and compared. This is compatible with a piecemeal rotation strategy. However, the choice of strategies used during mental rotation has shown to depend on individual factors, such as mental imagery abilities. According to Just and Carpenter (1985) individuals with high spatial abilities are able to mentally rotate around arbitrary, task-dependent axes and are usually faster in solving the tasks whereas individuals with low spatial abilities mostly rotate around standard axes. In a study with college students, Khooshabeh et al. (2012) found that individual, high imagery abilities predicted holistic rotations of figures by default (with switches to piecemeal transformation when required), whereas low imagery students chose piecemeal transformations straight away. Khooshabeh and Hegarty (2010) argue that a limited working memory capacity influences the choice of the rotation strategy and performance because less spatial transformation can be stored. Thus, individuals with low and high spatial imagery abilities can differ in their main data structures (representation of shapes) as well as in their rotation strategies.

It remains an open question, however, if the choice of physical rotation strategy similarly depends on individual differences in mental imagery abilities as the choice of mental rotation strategy does. Moreover, there is further research needed examining the use of technologically supported spatial training for different learner characteristics.

Aims and research questions

The first main goal of the current study is to examine to what extent physically rotating 3D figures has an effect on students' success, motivation, mental effort, and efficiency. The second main goal is to analyse the physical rotation processes based on the interaction data in more detail and to examine the influence of students' mental rotation ability on physical rotation success.

We base our research questions on the following assumptions: (1) mental rotation processes induce loads in working memory and can thus lead to cognitive overload. To reduce or prevent an overload, (2) physical rotation can be used to support solving mental rotation tasks; the effect is by offloading necessary spatial transformations from solely mental processes to external representations and motor processes. (3) Based on captured interaction data during the solving of the tasks, different rotation behaviours can be derived.

We compared the solving of physical rotation tasks on a tablet using touch-based interaction with a static mental rotation version on a tablet. Our approach involved, first, determining how mental and physical rotation compare to one another for 12–13-year-olds regarding achieved performance levels, task efficiency, mental effort involved, and students' motivation. Specifically, we were interested in establishing whether the familiarization effect found for 8–10-year-olds (Zander et al. 2016) would still exist for 12–13-year-olds, or whether mental spatial abilities would be mature enough to benefit from the offloading offered by physical rotation without familiarization effect. It also involved, secondly, a focus in scope on processes carried out during physical rotation and a focus in method on how students respectively start and end a physical rotation, as well as on what happens in-between.

Based on previous findings from Zander et al. (2016), we hypothesize that:

- The success rate will comparable between both groups (no familiarization effect) (H1a)
- The success rate will be generally higher in the physical condition (touch-based interaction, offloading) than in the mental condition (no touch-based interaction, no offloading) (H1b).
- Being able to physically rotate figures during the tasks will cause students to be more motivated than in the static version (H2).
- Physically rotating the figures, rather than rotating them mentally, will lead to lower levels of mental effort (H3).
- We want to analyse if students can solve the tasks more efficiently when using touch-based interaction compared to no interaction. We assume that task efficiency will be higher in the physical condition (H4).

In a second step, we will analyse interaction data captured during the solving of tasks. Based on students' individual success levels, we will examine the amount of physical rotation and the number of drags, as well as the point in time at which students started rotating figures. For this, we will combine data on success rate, effort and motivation with process data in order to analyse individual ways of problem solving. We assume that differences exist between the respective rotation behaviours of students with high and low success rates.

Study: methods and materials

This section describes the design and implementation of the study. We will explain how our iPad app works and how the touch-based interaction was implemented.

Touch-based interaction with our iPad app

To capture times, answers and interactions, we developed an iPad app (Fig. 2). During a task, a pair of 3D cube figures is presented next to one another with two answer buttons below. Subjects had to judge if the figures are identical or not by either pressing “Ja” (Yes) or “Nein” (No).

During the *physical* condition, subjects are able to rotate the right-hand figure using the Arcball technique (Shoemake 1992). This technique allows to intuitively rotate a 3D object using 2D touch input on the tablet (Fig. 3).

In contrast, neither figure could be rotated during the *mental* condition. For task construction, we used the same set of stimuli as Gardony et al. (2014), which was in turn taken from Peters and Battista (2008). Based on 15 figures and their mirror images, 120 different, pairwise comparisons with varying initial angular disparities among the pair were created.

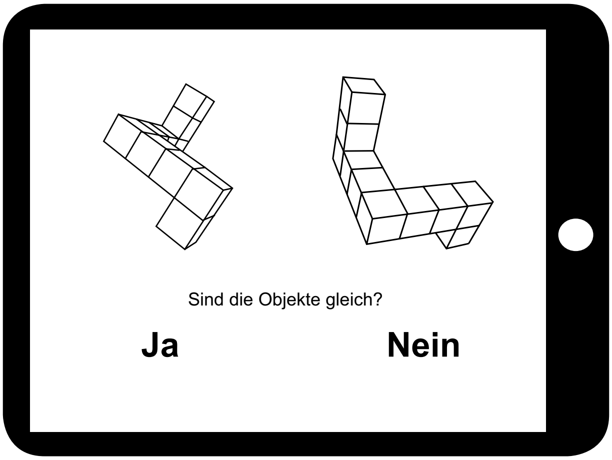

Fig. 2 A screenshot of the iOS app used in our study. The right-hand side figure was made rotatable during the physical condition

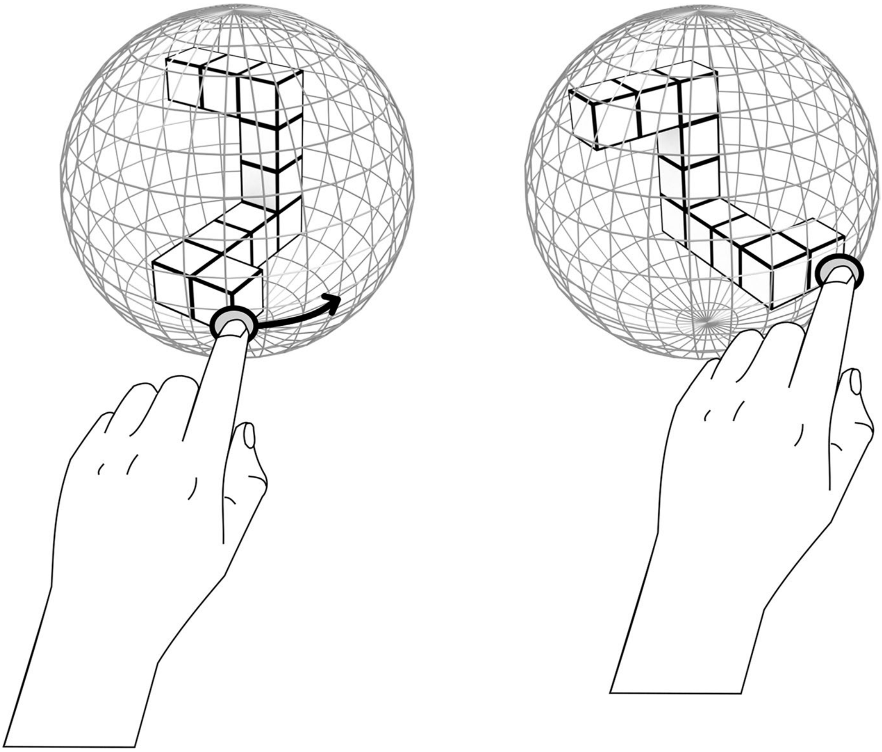

Fig. 3 Schematic illustration of the implemented Arcball technique for physically rotating the 3D figure

Participants

Forty-nine students (male = 22, female = 27, mean age: 12.6 years) from two secondary schools in Weimar, Germany, participated in our study. All students were used to iPads and used them regularly in class. We followed the principles outlined in Standard 8 of the Ethical Principles and Code of Conduct for Psychologists (American Psychological Association 2002) and obtained prior informed consent from students, parents, and school authorities.

Measures

Control variables

Students' initial spatial skills were assessed using the card rotation (Ekstrom et al. 1976) and the cube comparison tests (Ekstrom et al. 1976). We chose these tests, as both were shown to highly correlate with mental rotation skills in previous studies (e.g., Hegarty and Waller 2004). To control for students' current motivation before starting the app, we used the *Questionnaire to Assess Current Motivation in Learning Situations* (QCM) by Rheinberg et al. (2001). This questionnaire consists of 18 questions that load onto four scales, measuring current motivation relating to expected success, perceived challenge, current interest in the specific task, and anxiety of failure.

Dependent variables

Mental effort was measured based on the SVE—Scale for Validating the Recording of Subjectively Experienced Effort (Eilers et al. 1986): “How much effort did you invest to solve the task?”. Participants gave answers on a visual analogue scale from 0 = “no effort” to 220 = “exceptional effort”. Intrinsic motivation was measured with seven questions on a scale from 1 = “strongly disagree” to 7 = “strongly agree” based on Isen and Reeve (2005) (e.g., “It is interesting”; “It makes feel curious about it”; “It is enjoyable”). Correct answers, time per task, object rotations, and user interactions were automatically logged by the app. The efficiency score was calculated as the ratio of the number of correct answers and time per task, such that the score indicates the number of correctly solved tasks per second.

Procedure

The experiment was split into two sessions on two different days to avoid possible fatigue from pre-tests (see Fig. 4). In the first session, students completed the card rotation and the cube comparison tests. Each test is paper-based, consisted of two parts and had a time limit of 6 min. In the second session, students were randomly assigned to one of the two groups, *mental_physical* (MP) or *physical_mental* (PM). Both groups solved mental and physical rotation tasks on the iPad, but in different order. Group MP started with the mental condition in the first trial block and continued with the physical condition in trial block 2. Group PM started with the physical condition and continued with the mental condition. Before starting with the main test, students' initial spatial skills as well as their current motivation in learning situations were assessed. The QCM was presented at the beginning of the main test, right after the students were instructed about what kind of tasks they would have to solve.

During the main part of the study, we used a mixed within- and between-subjects design to compare motivation, mental effort, performance and rotation behaviour between the two different groups (MP and PM) at two points of measurement. The within-subjects

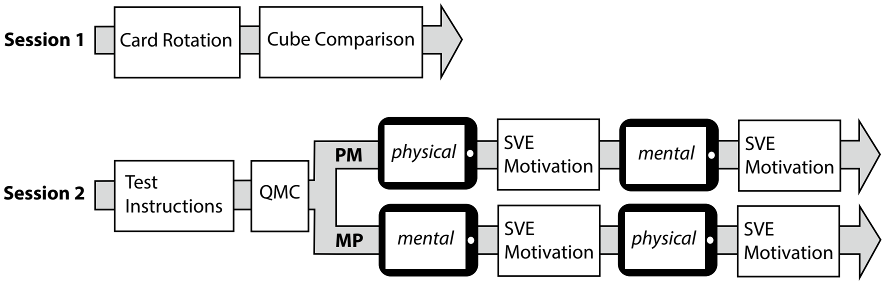

Fig. 4 An illustration of the experimental setup. The experiment was split into two sessions: session 1 lasted approximately 10 min and consisted of two pre-tests for assessing students' baseline spatial skill. During session 2, students were assigned to two experimental conditions (MP and PM). This session lasted approximately 60 min

comparison compensates for individual learning preconditions and controls for systematic training effects. Two different sets of tasks were used during the experiment, each containing 60 tasks with varying initial angular disparity between figures ranging from 0° to 180°.

Students of the two groups were tested simultaneously but in separate classrooms. Before each first trial block, students received detailed instructions about the task and they worked on five warm-up tasks to familiarize themselves with the type of task and the procedure. For the warm-up tasks, feedback was displayed about whether a task was solved correctly or not. Participants were instructed to work as quickly and precisely as possible. For tasks in the two main trial blocks, no feedback was given. After participants had finished a trial block, they filled in the SVE and motivation questionnaires.

Results

We used a MANOVA to explore effects of the within-group independent variable *trial block* and the between-group independent variable *group*. The alpha level was set to $\alpha = 0.05$. Bonferroni correction was applied to all post hoc *t* tests to correct for family-wise error. Effect sizes are reported for significant tests as ω^2 for ANOVAs (with 0.01 as small, 0.06 as medium, and 0.14 as large effect), and d for *t* tests (with 0.2 as small, 0.5 as medium, and 0.8 as large effect). Before analysing the scores of the QCM questionnaire and the intrinsic motivation, we calculated Cronbach's alpha to verify the reliability of the instrument. According to (Streiner 2003), values above 0.7 indicate a reasonable reliability. For the QCM we calculated Cronbach's alpha for all four subscales (success: 0.72, interest: 0.88, anxiety: 0.78). We chose to exclude the subscale for challenge from further analyses based on its low alpha value of 0.19. For intrinsic motivation, values are 0.93 (1. trial block) and 0.95 (2. trial block).

Control variables

Scores for card rotation ($t(42.8) = 0.392$, $p = 0.699$) and cube comparison tests ($t(47) = 0.485$, $p = 0.630$) did not differ significantly between the two groups. The scores of the QCM on the subscales interest ($t(47) = -0.465$, $p = 0.644$), probability of success ($t(47) = 0.152$, $p = 0.880$), and anxiety ($t(47) = 1.036$, $p = 0.306$) did not differ significantly between the two groups. These results indicate that initial spatial skills as well as the current motivation was comparable between the groups.

Main effects

Using Pillai's trace, we found no significant effect for the between-subjects factor *group* ($V = 0.042$, $F(4, 44) = 0.483$, $p = 0.748$, see the left-hand side of Table 1 for means and standard errors). This indicates that the distribution of students' mental and physical rotation skills did not differ between both groups.

A significant effect was revealed for the within-subjects factor *trial block* ($V = 0.435$, $F(4,44) = 8.455$, $p < 0.001$, $\omega^2 = 0.435$). Table 1 (right-hand side) shows means and standard errors of the within factor *trial block* independent of the respective interaction format (mental/physical) and *group* (MP/PM). Univariate within-subjects tests revealed no significant effects for success rate ($F(1, 47) = 0.565$, $p = 0.456$) and mental effort ($F(1,47) = 0.364$, $p = 0.549$), but did reveal significant effects for motivation ($F(1,47) = 4.244$, $p = 0.045$,

Table 1 Means and standard errors of between factor *group* (left-hand side) and of within factor *trial block* (right-hand side) for all dependent variables

	Group MP (N = 25)		Group PM (N = 24)		Trial block 1 (N = 49)		Trial block 2 (N = 49)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Success rate (%)	83.9	1.7	82.3	1.7	83.5	1.2	82.7	1.4
Motivation	4.6	0.33	4.6	0.33	4.7	0.25	4.3	0.25
Mental effort	9.49	0.95	8.76	0.94	8.96	0.739	9.29	0.692
Efficiency	0.094	0.005	0.101	0.005	0.09	0.003	0.105	0.005

$\omega^2 = 0.083$) and efficiency ($F(1,47) = 19.327$, $p < 0.001$, $\omega^2 = 0.291$). While motivation decreased significantly from trial block 1 to trial block 2, efficiency increased. In combination with the finding that the success rate remains on a comparable level between trial blocks, this increase in efficiency indicates that students were simply able to solve the tasks faster but did not improve effectiveness.

Interactions

Our analysis revealed a significant multivariate effect across the interaction between *group* and *trial block* ($V = 0.725$, $F(4, 44) = 34.665$, $p < 0.001$, $\omega^2 = 0.759$). Subsequent univariate tests showed significant interactions for success rate ($F(1, 47) = 0.292$, $p < 0.001$, $\omega^2 = 0.683$), motivation ($F(1,47) = 5.390$, $p = 0.018$, $\omega^2 = 0.114$), and mental effort ($F(1, 47) = 47.892$, $p < 0.001$, $\omega^2 = 0.505$). There was no significant difference for efficiency ($F(1, 47) = 0$, $p = 0.238$). To gain additional information about the sources of these interactions, we performed paired and independent *t*-tests for all four dependent variables. Due to the number of post hoc *t*-tests, we adjusted the alpha level to 0.0125 using Bonferroni correction (Table 2).

H1a, b—success rate

The paired *t* tests revealed significant differences with large effects for success rates for both groups. In both cases, success rates were higher in the physical condition. Respectively, comparing mental trial blocks and physical trial blocks overall revealed no significant differences (mental: $t(47) = 0.357$, $p = 0.723$; physical: $t(47) = 0.831$, $p = 0.410$). Thus, success in both conditions was independent of presentation order (H1a). Based on these results, we can also accept H1b, telling us that higher success rates were revealed for the physical condition.

H2—motivation

Overall, the values for motivation are high in both groups. The data shows that motivation remained nearly on the same level from trial block 1 to 2 for group MP, while it clearly decreased for group PM. An overall comparison of motivation in both trial blocks revealed no significant differences (mental: $t(47) = 1.009$, $p = 0.318$; physical: $t(47) = -0.521$, $p = 0.605$). As motivation did not significantly increase in group MP when solving tasks

Table 2 Means and standard errors and test statistics for both groups MP (*mental/physical*) and PM (*physical/mental*) (between-subject) and for both trial blocks (within-subject) for all dependent variables (number of participants group MP: N = 25; group PM: N = 24)

	Group vs. trial				
	Trial block 1		Trial block 2		Paired *t* test
Group	Mean	SE	Mean	SE	
Success rate (%)					
MP	78.8	1.7	88.9	1.9	t(24) = − 8.088, p < 0.001*, d = 1.17
PM	88.1	1.8	76.3	2.0	t(23) = 6.555, p < 0.001*, d = 1.13
Independent *t* test	t(38.365) = − 3.772, p = 0.001*, d = 0.93		t(47) = 4.567, p < 0.001*, d = 1.32		
Motivation					
MP	4.5	0.35	4.6	0.36	t(24) = − 0.283, p = 0.780
PM	4.9	0.36	3.9	0.36	t(23) = 3.195, p = 0.004*, d = 0.56
Independent *t* test	t(47) = − 0.645, p = 0.522		t(47) = 1.208, p = 0.233		
Mental effort					
MP	11.24	1.02	7.72	0.93	t(24) = 4.860, p < 0.001*, d = 0.71
PM	6.67	1.06	10.85	1.02	t(23) = − 4.929, p < 0.001*, d = 0.82
Independent *t* test	t(47) = 3.094, p = 0.003*, d = 0.89		t(47) = − 2.262, p = 0.028, d = 0.65		
Efficiency (correct answers/time)					
MP	0.084	0.005	0.104	0.006	t(20) = − 4.234, p < 0.001*, d = 0.69
PM	0.095	0.005	0.105	0.006	t(23) = − 2.122, p = 0.045, d = 0.41
Independent *t* test	t(39.344) = − 1.751, p = 0.87		t(47) = − 0.298, p = 0.767		

*Denotes significant differences after applying the corrected alpha level of 0.0125 with the physical condition, we cannot accept H2, which stated that motivation will be overall higher in the physical condition.

H3—mental effort

Data for mental effort shows large significant differences for both groups between trial block 1 and trial block 2. While the values for mental effort in trial block 1 differ significantly with a large effect in favour of the physical condition, differences for trial block 2 are slightly smaller but not significant. However, a comparison between mental and physical conditions overall in both trial blocks did not reveal significant differences (mental: $t(47)=0.267$, $p=0.791$; physical: $t(47)=0.745$, $p=0.460$). As the difference in trial block 2 was not significant, we can only partially accept H3, indicating that physical rotation produced lower levels of mental effort.

H4—efficiency

Efficiency was defined as the ratio of the number of correct answers and the overall time spent on these tasks. For both groups, efficiency increased from first to second trial block. However, this difference is only significant for group MP. This data can be explained through an overall speedup during the solving of the tasks; success did not increase for both groups from trial block 1 to trial block 2. Comparing mental and physical conditions over both trial blocks revealed no significant differences ($t(34.862)=1.169$, $p=0.250$). However, efficiency was significantly higher for the mental condition in the second trial block ($t(47)=-2.799$, $p=0.007$, $d=0.82$) compared to the mental condition in the first trial block. This indicates the existence of an ordering effect regarding the time on task for the mental condition. Thus, we cannot accept H4, as efficiency was not generally higher for the physical condition.

Angular disparity effect

As discussed in Sect. 2.3, many classical mental rotation studies reported an angular disparity effect (ADE). To examine if the ADE is present in our data, also for physical rotation, we analysed all valid mental and physical *same* tasks. Time on task significantly correlates with initial angular disparity for both the mental condition ($r=0.284$, $p<0.001$) and the physical condition ($r=0.329$, $p<0.001$). Both strengths of correlation are comparable to those found by Gardony et al. (2014). Figure 5 depicts the relation between time on task and initial angular disparity as aggregated in 30° steps. Both the mental and physical conditions show linear increases on time on task when the initial angular disparity increases.

In summary, it can be stated that using the app in the physical condition leads to higher success rates, to lower mental effort, and to higher efficiency than using the purely mental condition. Regarding motivation, no general effect of condition was found. As expected, we found an ADE for mental and physical rotation tasks, indicating, among others, a similarity of processes involved in mental and physical rotation. We will next analyse the observed physical rotation behaviours in more detail, with an emphasis on individual properties of task solving processes.

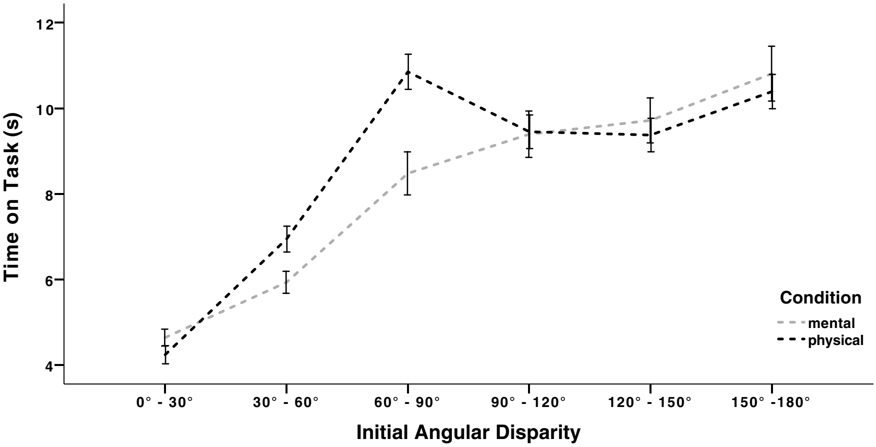

Fig. 5 Mean times for physical and mental rotation tasks dependent on the initial angular disparity (error bars indicate the standard error)

Differences in physical rotation behaviour

Our app logs each interaction with the iPad during the tasks in the physical condition and thus allows us to analyse the actual physical rotation processes. We were especially interested in differences of rotation behaviour between students who achieved high success rates and students with low success rates. As criterion for distinguishing low and high achievers, we used their success rate during physical rotation. Since, in the preceding analysis, we found no significant differences regarding success, motivation, mental effort, and efficiency between the physical conditions in both groups, we pooled all valid physical task data for the analysis. Of particular interest are the differences between students at both ends of the performance range. To increase the contrast between low and high achievers, we thus chose to examine all students whose physical rotation success rate was respectively at least one standard deviation above or below the mean. The resulting highest-success group included six students (success rates higher than 96.3%). Similarly, the resulting lowest-success group also included six students (success rates lower than 80.7%).

Pre-test and main test performance

On a descriptive level, data for initial motivation and pre-test scores indicate that low achievers had a much lower interest and reported a lower probability of success before solving the tasks (see Table 3). The reported anxiety was slightly higher for low achievers. Low achievers also accomplished much lower scores in both pre-tests, indicating that their spatial skills were lower in the first place.

Table 4 shows data for success, motivation, mental effort, and efficiency during the physical condition of the main test for low and high achievers. Descriptively, the data show much lower values for motivation of low achievers as well as much higher values for mental effort. Interestingly, values for efficiency were almost equal between both groups. Although low achievers solved fewer tasks correctly, they were relatively fast in doing so

Table 3 Means and standard errors of initial motivation and pre-test scores for low and high achievers

	High achievers (N = 6)		Low achievers (N = 6)	
	Mean	SE	Mean	SE
Interest (QCM)	4.7	1.6	2.3	1.1
Probability of success (QCM)	4.5	1.2	3.1	1.5
Anxiety (QCM)	2.9	1.2	3.6	1.9
Card Rotation	68	22.8	40.3	45.1
Cube Comparison	15.3	3.5	− 6.2	14.4

Table 4 Means and standard errors of success, motivation, mental effort and efficiency for the physical condition for low and high achievers

	High achievers (N = 6)		Low achievers (N = 6)	
	Mean	SE	Mean	SE
Success rate (%)	98.3	1.8	72.2	7.6
Motivation	6.5	0.3	4.7	0.9
Mental effort	2.9	1.4	8.7	2.4
Efficiency	0.1	0.007	0.08	0.004

Table 5 Means and standard errors of rotation variables for tasks from students with high and low success rates

	Tasks of high success students (N = 359)		Tasks of low success students (N = 360)		Paired *t* test
	Mean	SE	Mean	SE	
Time per task (s)	9.3	0.26	8.7	0.29	t(717) = 1.626, p = 0.104
Number of drags	5.8	0.23	3.5	0.2	t(694.6) = 7.419, p < 0.001*, d = 0.56
Time until first drag started (%)	20.9	0.6	19.3	1.0	t(605.5) = 1.361, p = 0.174
Time until last drag ended (%)	82.2	1.1	60.8	2.1	t(548.5) = 8.730, p < 0.001*, d = 0.75
Accumulated way (°)	401.6	16.4	319.9	19.2	t(717) = 3.232, p = 0.001*, d = 0.24

*Denotes significant differences (α = 0.05)

(cf. time on task from Table 5). Since efficiency is the ratio of correctly solved tasks and the time spent on solving them, both groups achieved very similar efficiency values.

Rotation behaviour

Next, we analysed data on low and high achievers' rotation behaviour. The measures included: *Number of drags* counts any occurrence of setting the finger down on the tablet and taking it up again. A*ccumulated way* is an angular measure of how far an object is rotated across an entire task, irrespective of rotation direction. We further analysed at which point of time students started to rotate an object and for how long they rotated before they gave the answer. In all, we compared 359 tasks from the six high achievers with 360 tasks from low achievers.

As can be seen in Table 5, tasks from low achievers did not differ significantly from tasks of high achievers regarding time on task and the point of time the rotation started. In contrast, tasks of low achievers showed significantly less drags and less accumulated way. Furthermore, the low achievers stopped their rotations as early as after 60% of the time on task. This leads to approximately three seconds less rotation time on average compared to the high achievers.

According to Just and Carpenter (1976), the mental transformation phase (2) lasts until an angular disparity of approximately 50° between the figures is reached. Based on the results of Gardony et al. (2014) and Zander et al. (2016), we have reason to assume that processes of solving tasks with physical rotation do work in a similar way. Therefore, for the present analyses, we assumed that students often rotated the figure until a low angular disparity was reached before giving their answer. And indeed, when we analysed final angular disparities we found that for low-achievers *same* tasks ended with a mean final angular disparity of 72.7° (SE = 4.3) whereas for high achievers *same* tasks ended with a mean final angular disparity of 31.7° (SE = 2.5).

Discussion and conclusion

With this study, we investigated differences and similarities of using and not using touch-based physical interaction on a tablet during Shepard and Metzler style rotation tasks. Specifically, we examined whether physically rotating 3D figures has an effect on task success and efficiency, motivation, and mental effort. In line with hypotheses, we found higher success and efficiency scores, and lower scores for mental effort when students used the physical rotation condition on tablets. Moreover, our data show consistently higher success scores for physical rotation (on average 10% higher than for mental rotation). The latter finding contrasts findings described by Zander et al. (2016) established for a much younger group of students; there, physical rotation only had an advantage over mental rotation once it had been preceded by mental rotation. Zander et al. (2016) interpreted such interaction as a sign that the employed 3D mental rotation tasks were a bit too difficult for their target group, possibly frequently inducing high cognitive load and an undirected, very explorative manner of using the app. Their interpretation is in line with reports by Jansen et al. (2013) on generally low mental rotation performance of primary school students when 3D stimuli are employed. The results of the present study show that our target group (secondary school students aged 12–13) was able to consistently solve physical rotation tasks irrespective of whether they had a familiarization with mental rotation tasks. This indicates that given an old enough age group physical rotation has robust, general benefits over mental rotation.

In a second step, we targeted specific sub-groups of the students in our study: the high- and low-achievers. We found that students with lowest levels of physical rotation success had reported higher values of anxiety and lower values of probability of success as well as of interest before even starting with the tasks. Data on their rotation behaviour revealed that they were on average not able to reach low angular disparities between the figures. This inability is crucial, however, as especially for students with low spatial skills, reaching low angular disparities seems to be an important predictor for task success.

Practical implications

Regarding wider implications for training applications, it is the low spatial ability students who could potentially benefit the most from an app that would adapt to their individual needs and skill levels. Such an adaptive app could, for example, detect difficulties during the solving process based on interaction data and could also offer hints for the user about how to rotate the figures to decrease angular disparity.

Our results (e.g., on the relation between final angular disparity and task success) add to the body of research that describes similarities between processes respectively involved in mental and physical rotation. If we add to this the finding by Adams et al. (2014) that physical rotation training can lead to improvements in mental rotation skills the potential of a future physical rotation app that would assess users' individual spatial skills becomes clear: it could provide a program that can be used to improve users' individual mental rotation abilities. Such a program could for example offer visual hints for low achievers to indicate the optimal rotation angle for decreasing the angular disparity. Conversely, high achievers could be provided with tasks where the rotation is limited which forces them to plan ahead their rotation and develop more efficient strategies.

Limitations of the study

It is important to keep in mind that our study has certain limitations. Crucially, the results for highest and lowest success students are derived based on small samples. The analysis of performance and motivation is thus only descriptive in nature. More robust is our inferential analysis of students' rotation behaviour, as discussed above.

Regarding the characteristic levels of success for physical and mental rotation, we cannot say if these levels will or won't prove stable when students practice these tasks over long periods of time. It is possible that the gap between success scores in physical and mental rotation may go away after prolonged training. To clarify this, a more long-term practice study is needed.

Future research directions

Moreover, several studies examined if the effects of mental rotation training can be transferred to other spatial problems (e.g., Chu and Kita 2011). In order to examine similar effects for our app, it would be necessary to conduct a training study and analyses transfer effects of physical rotation to other spatial tasks.

On a related note, low achievers reported lower values than high achievers in regard to motivational variables, such as interest and probability of success. Various studies have stressed the importance of motivation variables for learning (e.g., Schunk and Zimmerman 2008). It thus seems probable, that a future individualized physical rotation training app might address motivational needs by integrating an additional mechanism for activating and maintaining motivation levels in order to be effective.

For the current analysis of the rotation behaviour, we pooled data of students' physical tasks. This results in a general trend of the rotation behaviour but covers individual strategies. Therefore, future work should focus more on an analysis of students' individual rotation behaviour. An analysis of rotation trajectories to extract underlying problem-solving strategies seems particularly promising. This may, in turn, form the bases for classification of students based on profiles of strategy use.

To conclude, findings from our study point to a number of beneficial effects for secondary school students through using our app. We assume that physical rotation can be used as a proxy for the study of mental rotation processes and that using physical rotation-based research will contribute to further understanding mental rotation processes and strategies.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest. The used iPad app was exclusively developed for the internal use during the experiments. The app is not available for users outside our lab. The authors did not receive any commercial or reputational benefit for the app.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institution and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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