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ORIGINAL ARTICLE

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What makes tablet-based learning effective? A study of the role of real-time adaptive feedback

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This study investigated the added value of real-time adaptive feedback on seventh graders' performances in tablet-based geometry learning. To isolate the effects of the medium (ie, tablet) from those of the feedback, three groups were compared: paper-and-pencil, pen-based tablet without feedback and pen-based tablet with feedback. The feedback was provided by a tutoring system based on an artificial intelligence that automatically interpreted students' pen strokes on the screen. A total of 85 French students drew three geometric shapes, either on paper or on a tablet, and then performed a transfer task on paper. Results showed that using a tablet without feedback did not improve learning but seemed to enhance interest in the task compared to the paper-and-pencil group. Students in the tablet with feedback group performed significantly better than the other two groups on learning, as well as on transfer. This study was the first to combine media comparison and added-value approaches to test the effects on students' geometry performances of using a new educational app on a pen-based tablet in a naturalistic classroom environment. Results showed that it was not the medium used but the intelligent tutoring system-based feedback that improved students' performance. Our data therefore indicate that artificial intelligence is a promising way of providing learners with real-time adaptive feedback in order to improve their performances.

KEYWORDS
adaptive feedback, artificial intelligence, geometry app, intelligent tutoring system, learning performances, tablet computer

Practitioner notes

What is already known about this topic

- Previous meta-analyses have investigated the effects of tablet-based learning.
- Tablet computers have been proven to increase students' motivation.
- Yet, the influence of tablet computers on learning outcomes remains inconclusive.
- Other studies show that certain features of environments, such as feedback, have positive effects on learning.

What this paper adds

- Most of the previous studies adopted a media comparison approach (paper- vs. tablet-based instruction).
- We combine this approach with an added-value approach by adding or not real-time AI-based feedback.
- Results showed that tablet use increased children's interest but not their learning outcomes.
- Feedback improved children's performance in a training task and a later transfer paper task.

Implications for practice and/or policy

- Tablet computers can promote students' interest in the task during geometry instruction.
- App features play a critical role in improving students' learning.
- Specifically, IA-based adaptive feedback helps children to perform better on a geometry task.

INTRODUCTION

Tablet computers are being used more and more widely in educational settings (OECD, 2019). With the increasing presence of new technologies in the classroom and children's issues with mathematics, tablets could prove to be a useful means of helping students perform learning tasks (eg, Haßler et al., 2016) or enhancing learners' perceptions of instruction (eg, Hammer et al., 2021). These tools offer a wide range of features that could be used to assist learners. For example, recent progress in AI has made it possible to recognize the user's hand-drawn strokes and, as a result, to generate real-time corrective feedback in order to inform learners of their mistakes (Krichen et al., 2019, 2020). Based on this last finding, the present study investigated the effects of AI-based real-time feedback on seventh graders' learning when performing geometry exercises on a pen-based tablet. Its main purpose was to combine a media comparison approach to test and isolate the effects of the medium used to perform the task (paper vs. tablet) with an added-value approach whose aim was to address more specifically the effects of feedback.

Improving learning through the use of new technologies: The case of geometry

Geometry is a demanding area of mathematics that can lead learners to develop many different skills, including visualization, critical thinking, problem solving and deductive reasoning (Jones, 2002). Geometry is considered to be challenging as learning geometry requires high-level thought processes and students typically lack an understanding of geometry concepts (Cesaria & Herman, 2019). The Trends in Mathematics and Science Studies (TIMSS) international assessment, conducted by the International Study Center at Boston College, assessed fourth- and eighth-graders' performances in several areas of mathematics and science (Mullis et al., 2020). Results showed that students exhibited weaknesses in the content domain of geometry in almost 40% of the participating countries.

A second-order meta-analysis conducted by Young (2017) showed that technology-enhanced instructions can be effectively used to support mathematics achievement, as they engage students cognitively in the tasks they have to perform. Just as in computer games research (Mayer & Johnson, 2010), two approaches can be used to study educational digital devices: a media comparison approach where two different media are compared (pen and paper vs. digital device), and an added-value approach that tests the effects of the features of an educational document on students' information processing (see Mayer, 2019). For example, in the field of augmented reality-based learning, a systematic review recently showed that over 80% of studies applied a media comparison approach (Buchner & Kerres, 2023). Based on their review of the literature, the authors concluded that media comparison approaches have important methodological limitations, mainly because it is extremely complex to guarantee the same conditions in experimental groups with this approach, and researchers should recognize that learning environments can be effective, but not if they are poorly designed. They therefore recommended conducting more value-added studies to better understand when and how such environments are beneficial.

In the area of geometry learning, most studies have so far featured media comparisons, contrasting the traditional paper-and-pencil method using a classic geometric tool with a technology-based method using geometry tools on a specific app. In the study conducted by Dogan and İçel (2011), eighth graders underwent a 2-week geometry course, and half of them performed these activities with the GeoGebra interactive application on a computer. Results showed that performing GeoGebra activities positively enhanced students' achievement. These results replicated those of Saha et al. (2010), who showed that mathematics achievement was greater in a group that was taught coordinate geometry using GeoGebra than in another group that was taught these concepts in a traditional way. More recently, Hwang et al. (2020) have shown that using a tablet PC ubiquitous geometry system improved students' geometry learning performances compared to using traditional geometry tools. Their study demonstrated that the use of the tablet PC system led to high learning motivation. Therefore, the use of interactive software appears to be a good way of improving students' achievement in the area of geometry learning (eg, Chang et al., 2014; Di Paola et al., 2013).

Tablet computer use in the classroom

As mentioned above, there has been an increase in tablet use in schools (OECD, 2019). However, there has been only limited research on its effects on children's learning performances in a classroom setting. More specifically, as shown by Haßler et al. (2016) and Wakefield et al. (2018), most of the studies have focused on assessing learners' attitudes and feelings about this tool, without evaluating the effects of its use on learning outcomes.

A recent study also showed that using tablets in classrooms during 4 months increased learners' perception of instruction (Hammer et al., 2021). Other studies have revealed that students and teachers have a positive perception of tablets (eg, see Mulet et al., 2019, for a review), reporting that these tools can increase students' motivation, which is known to be critical for the learning process (Mayer, 2014). In the systematic literature review on iPad use in higher education conducted by Nguyen, Barton and Nguyen et al. (2015), results showed that iPads enhance students' learning experience, but not necessarily their learning outcomes.

In another review published 1 year later, Haßler et al. (2016) analysed the influence on learning outcomes of tablet use in primary and secondary schools. Of 23 studies, 16 supported the benefits of tablet use on learning performances, 5 showed no difference and 2 reported negative effects. Moreover, as Haßler et al. (2016) concluded, more rigorous methods and experimental designs are needed to better understand these effects on learning outcomes. The above-mentioned research focused on comparing the effects of each medium on students' learning (media comparison approach). However, it is critical to assess what the medium itself brings to the learner or how it changes the learning situation, in order to fully understand its effect.

In their recent meta-analysis, Güler et al. (2022) observed a medium positive effect of mobile learning use (eg, tablet, handheld devices and phones) on mathematics achievement, but only 6 of the 22 studies they analysed focused on geometry, and only 3 of these involved primary school students. For example, in the study published by Fabian et al. (2018), 52 students in sixth and seventh grades participated in collaborative geometry learning activities over 3 months. Almost half of them used tablets, while the others performed similar paper-based activities. Results revealed a positive effect of tablet-based activities on learning achievement. In a more recent study (Fabian & Topping, 2019), 74 students in fifth and sixth grades participated in active and collaborative geometry activities with or without tablets over a 6-week period. Contrary to the previous study, results failed to reveal a difference between the groups on posttest achievement scores. So, given our current state of knowledge, we can only conclude that the effects of tablet use on geometry learning are mixed for young students.

Providing feedback on a tablet computer to improve learning

Studies have sought to promote students' learning in geometry by providing guidance or by scaffolding their work with feedback. A wide range of research has investigated the effects of guidance in geometry in the form of worked examples, demonstrating that these can enhance learning, compared with more traditional methods (eg, Bokosmaty et al., 2015; Chen et al., 2015, 2016; Retnowati et al., 2010). Other studies have shown that providing feedback can also be a way of enhancing students' learning when working on geometry problems (eg, González & DeJarnette, 2015). As stated by Hattie and Timperley (2007), feedback is one of the most powerful influences on learning and achievement, but this impact is highly dependent on the kind of feedback used.

More recently, a meta-analysis of 435 studies (Wisniewski et al., 2020) confirmed this beneficial effect of various types of feedback (reinforcement/punishment, corrective feedback and high information feedback) on learning, although this effect was negative in 17% of studies, with a medium effect size ($d = 0.48$). This meta-analysis also showed that reinforcement/punishment feedback is less effective than corrective and/or high information feedback. Two other recent reviews have shown that while there are many theoretical models of feedback, it is possible to identify a number of common features (Lipnevich & Panadero, 2021; Panadero & Lipnevich, 2022). Based on these theoretical models, these authors defined feedback as 'information that includes all or several components: students' current state, information about where they are, where they are headed and how to get there, and can be presented by different agents (ie, peer, teacher, self, task itself, computer). This information is expected to have a stronger effect on performance and learning if it encourages students to engage in active processing' (Lipnevich & Panadero, 2021, p. 25). According to them, feedback can be characterized by its content (verification of the answer and valence), its functions (effects on learning performance, motivation or self-regulated learning), its mode of presentation (immediate or delayed) and the source of the feedback (teacher, peer and computer). Thus, if students receive feedback about the correctness of their answers, they will know whether they are managing the task and be able to rectify their answers accordingly (see also Azevedo & Bernard, 1995). For instance, in a geometry exercise, if parts of students' drawings are coloured in red or green, depending on their correctness, they will know what they have to erase and redraw. By redrawing the incorrect parts of a geometric shape, they will reduce the gap between their initial performance (incorrect drawing) and the desired goal (geometric shape drawn correctly). It can be regarded as adaptive scaffolding, as feedback is generated by an artificial intelligence (AI) system that analyses students' performances over time and provides support (in the form of corrective feedback) during learning (Azevedo et al., 2004). Without the use of technology, feedback has to be provided by either teachers or peers, which prevents learners from receiving real-time corrective feedback at each step of their performance.

Paradoxically, a recent meta-analysis showed that only a few studies have investigated the use of AI systems in primary school to promote students' learning (Zheng et al., 2021). Moreover, researchers recently highlighted the fact that there is little research investigating the effects of intelligent tutoring systems in the area of geometry (see Mousavinasab et al., 2021, for a review of these systems in education), as well as a dearth of research on the effects of adaptive feedback on learning (see Maier & Klotz, 2022, for a review). The recent meta-analysis conducted by Güler et al. (2022) also brought to light that only a few studies were conducted to assess the effects of tablets on geometry learning. Therefore, our research aimed to deepen our knowledge of adaptive feedback on primary school students' performances in the area of geometry using a tablet-based intelligent tutoring system.

Research objectives and hypotheses

In sum, most of the above-mentioned studies on tablet-based learning adopted a media comparison approach (traditional methods vs. technology-enhanced instructions). Moreover, the few studies to have explored the effects of tablet computer use on children's learning yielded mixed results (Haßler et al., 2016; Nguyen et al., 2015). Media comparisons are not always reliable, as learning situations involve more than simply a change of medium. When a traditional method (pen and paper) is compared with a technology-based one, the accompanying app may introduce new features that are not present in the traditional method. Therefore, the positive effects observed may stem either from the medium used or from the design features of the software (Herodotou, 2018). We believe it is critical to control for these variables, in order to contrast the traditional method with the most comparable learning situation using a different medium. If features are added to the app, a new group should be included in the study (added-value approach). Without further changes, the medium per se does not add much for learners, except perhaps the novelty of the situation, which may explain learners' positive attitudes towards tablet use.

The main purpose of the present study was to combine a media comparison approach with an added-value approach in order not only to test the effects of the medium itself (with no further changes) but also to distinguish between the effects of one specific feature of the software (real-time corrective feedback) and the effects of the medium used to perform the task. The study's first objective was therefore to compare the effects of the medium used (paper-and-pencil vs. pen-based tablet) on students' drawing of geometric shapes (media comparison approach). A new geometry app called IntuiGéo designed by the authors was used in this study (Krichen et al., 2019, 2020).

The second objective was to assess the effects of providing real-time corrective and adaptive feedback on students' learning performances (added-value approach). To this end, students in the third study group used the same application but received feedback based on the AI system's interpretation of their drawing on screen. According to Hattie and Timperley (2007), feedback can be defined as 'information provided by an agent regarding aspects of one's performance or understanding' (p. 81). Based on feedback models and the recent typology of their features (Lipnevich & Panadero, 2021; Panadero & Lipnevich, 2022), the corrective feedback used here primarily served a learning and performance purpose. More specifically, the AI-based intelligent tutor provided real-time visual feedback during exercises. For example, as soon as a student had finished drawing a segment or an angle, this part of the geometric shape turned red if it was incorrect or green if it was correct (see Figure 1).

To our knowledge, the present study was the first to combine these approaches to test the effects of using a new educational app on a pen-based tablet computer on students' performances in geometry in a naturalistic environment. Simply changing the medium used to perform a learning task (paper-and-pencil vs. tablet computer) may not be sufficient to affect students' learning performances (Clark, 1983). Another argument for this comparison is that the use of a geometry application on a pen-based tablet was very new for the students and might consequently have generated usage difficulties for them (eg, drawing figures on the screen using a stylus and virtual tools). Comparing paper-based and tablet-based conditions featuring the same tools (real or virtual, according to condition) allowed us to assess these potential difficulties and, by so doing, isolate the effect of medium from the effect of feedback. Had we not taken this precaution, it might have been argued that the feedback simply compensated for the difficulties introduced by the medium, thereby considerably reducing the practical implications of our study. In light of these arguments and the mixed results reported in previous similar studies (Fabian et al., 2018; Fabian & Topping, 2019), we did not expect to observe any differences regarding learning performances between the paper-and-pencil group and the tablet without feedback group.

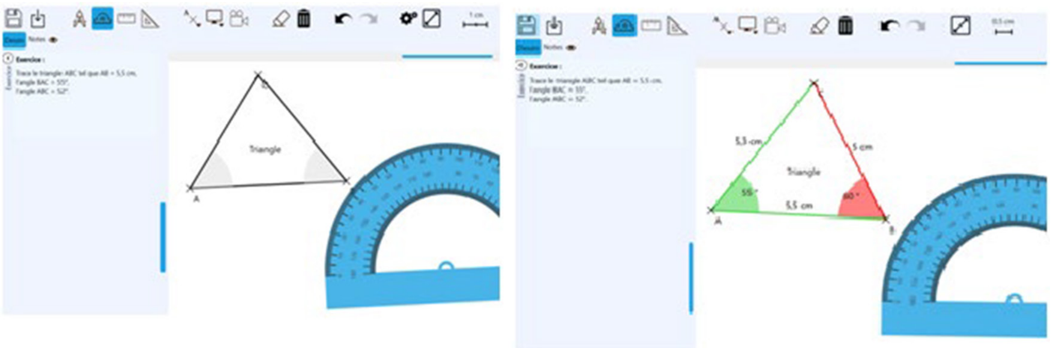

FIGURE 1 Screenshots of the pen-based tablet computer with the IntuiGéo app: tablet without feedback (left) and tablet with real-time corrective feedback (right).

However, as the presence of corrective feedback can improve students' learning performances (Hattie, 2008), in relation to Objective 2 (added-value approach), we expected participants in the tablet with feedback group to draw the geometric shapes better than those in the tablet without feedback and paper-and-pencil groups (H1). We also expected them to make fewer mistakes with the angles (ie, discrepancies between angles actually drawn and required angles) (H2). Moreover, we expected these positive effects to extend to a transfer task for a similar geometric shape (H3a), as well as a different geometric shape (H3b). These hypotheses therefore predicted better learning performances for the tablet with feedback group than for the other two groups.

According to Eutsler et al. (2020), using a tablet computer may increase children's interest in the task, owing to the device's novelty. Thus, previous results regarding learners' attitudes towards tablet computers (eg, Mulet et al., 2019) led us to predict that the two tablet groups would report greater interest in the learning task and regard it as more entertaining, compared with the paper-and-pencil group (H4).

METHOD

Participants

Invitations to take part in the study were sent to students' parents. Those who agreed to their children taking part in the study signed a consent form that explained the overall aim of the study. We obtained written informed parental consent for each student before starting the experiment which was conducted in accordance with the principles of the Declaration of Helsinki and following the American Psychological Association Ethical Principles of Psychologists and Code of Conduct. As a result, a total of 85 seventh graders (39 girls and 46 boys) from a French classroom took part in this study (M_{age} = 11.94 years, SD = 0.28). The students came from three classes, all in the same school. Two different teachers were in charge of these classes. In each class, students were randomly assigned to one of the three study groups to avoid potential class or teacher effects. Based on the collected demographic data, we tested whether the three groups differed in gender ratio. Analysis did not reveal any significant difference among the three groups: $\chi^2(2) = 1.18$, $p = 0.553$, Cramer's $V = 0.118$. In the first group (paper-and-pencil group; $n = 27$), students drew geometric shapes on paper using classic geometry tools. In the other two groups, students drew the same geometric shapes on a pen-based tablet computer with the IntuiGéo app (see Appendix 1 for a description of the app). The IntuiGéo app imitates the natural behaviours of students drawing on paper: participants manipulated realistic virtual tools with their fingers and drew with a stylus. The functionalities provided by the app in the two tablet groups consisted of drawing and geometric tools, recognition of lines drawn with the stylus and attribution of letters to the geometric shapes (see Figure 1).

While they were drawing, they either received no feedback (tablet without feedback group; $n = 28$) or real-time corrective feedback (tablet with feedback group; $n = 30$). In the tablet with feedback group, segments and angles immediately turned green if they were correct (correct segment length and correct angle value), and red if they were incorrect (errors for the drawn segments or angles; see Figure 1). Except for this difference, the two tablet groups offered students the same functionalities on the app. All the students who participated in this study had had geometry lessons with their mathematics teacher before the experiment. The study was conducted in a French secondary school. All the instructions were provided in French, the students' mother tongue.

Material

The experimenter provided the students with paper and geometry tools: a ruler, a protractor and a set square. Students in the two pen-based tablet groups were provided with a Dell Latitude 5285 (12.3″) tablet computer and a Dell Active stylus.

Webcams were used to record the students' drawings of the geometric shapes in the paper-and-pencil group. In the tablet groups, students' drawings on the screen were recorded using software.

Training phase *(familiarization)*

Before they began the learning phase, students in all three groups underwent a brief training phase. Students in the two pen-based tablet groups were shown examples of how to use the IntuiGéo geometry app. These tasks took less than 6 minutes to perform. Students in the paper-and-pencil group performed the same tasks but on paper.

Measures

Pretest questionnaire: Demographic data

Before performing the exercises, the students completed a questionnaire to collect their demographic data (ie, sex and age).

Baseline assessment

Students had to rate their perceived geometry skills ('I consider myself to be a good pupil in geometry') on a 7-point Likert scale ranging from 1 (*Do not agree at all*) to 7 (*Totally agree*). They were then asked to perform a baseline assessment task (see Appendix 2), in which they had to draw a right-angled triangle on paper using the geometry tools that were provided. Students were given 4 minutes to perform this task. This task was designed to ensure that the three groups did not differ in their ability to draw geometric shapes.

The triangles drawn by the students were subjected to binary coding. Students either succeeded in drawing the geometric shape (correct length of the AB segment and correct angles for ABC and BAC; scored 1 point) or not (0 point). A margin of error of 1 millimetre for the segments and 1 degree for the angles was allowed. The total difference between the drawn angles and the correct ones was also measured for the drawn geometric shape.

Learning phase

During the learning phase, students had to draw three scalene triangles (see Appendix 2). Depending on their group, they drew these triangles either on paper or on a pen-based tablet. In order to draw each triangle, students had to draw a segment followed by two angles. Exercises were prepared in close collaboration with the mathematics teachers involved in the research project. Students were given 6 minutes to perform each geometry exercise. At the end of these 6 minutes, regardless of whether they had completed this exercise, they had to move on to the next one. The order of exercises was counterbalanced in each group, and each exercise had the same level of difficulty. The use of these three successive counterbalanced exercises enabled us to assess any progress made by the students over the course of the lesson.

Binary coding was used for the three exercises. For each exercise, students either successfully (1 point) or unsuccessfully (0 point) drew the triangle. Moreover, for each triangle, we measured the total difference between the drawn angles and the correct angles. This measure was calculated on the final geometric shape drawn by students.

Transfer task

After the learning phase, students in all three groups were asked to draw two new geometric shapes on paper. For this purpose, blank paper, a pencil and geometry tools (ruler, protractor and set square) were provided to each student. This transfer task was designed to assess students' ability to apply what they had learned to solve new problems (Fiorella & Mayer, 2015). They were therefore asked to draw a geometric shape they had practised drawing (ie, another scalene triangle and near transfer task). They were also asked to draw a new geometric shape they had not practised (ie, right-angled triangle, see Appendix 2). This last task was considered to be a far transfer task as it required students to use a slightly modified solution procedure as they needed to draw a right angle. Students started by drawing the scalene triangle for 4 minutes, then the right-angled triangle for 4 minutes.

Just as in the baseline assessment task, both triangles drawn by the students were binary coded. A margin of error of 1 millimetre for the segments and 1 degree for the angles was allowed. As before, the total difference between the drawn angles and the correct angles was calculated.

Interest in the task

After performing the transfer task, students responded to a questionnaire assessing their interest in the task. This questionnaire was composed of three items (eg, 'Performing these geometric exercises was interesting') adapted from Rotgans and Schmidt (2011, 2014). Students had to rate all the items on a 7-point Likert scale ranging from 1 (*Don't agree at all*) to 7 (*Totally agree*). Cronbach's alpha for this scale was $\alpha = 0.667$. Following Nunnally (1978), this Cronbach's alpha was just below the acceptable value of 0.70. Therefore, these data should be interpreted cautiously.

Procedure

Students were randomly assigned to one of the three groups and sent to the corresponding classroom. This study took place within the framework of the teachers' programme of mathematics lessons across the year, in a single session lasting about 50 minutes. Students were told that they would have to draw geometric shapes during the session, either on paper or on a pen-based tablet. They then responded to the questionnaire collecting demographic data and rated their perceived geometry skills. Next, students performed the baseline assessment task for 4 minutes. Participants then underwent a brief learning phase where they were asked to perform several drawings (ie, drawing of a segment and drawing of an angle). Software was then launched on the tablet to record the screen in the two tablet groups, while a webcam was used to record the students' drawing process in the paper-and-pencil group. Students were then asked to perform the three exercises making up the learning task. They had 6 minutes to perform each exercise. Next, participants performed the transfer task. Finally, students completed the interest questionnaire and were thanked for their participation.

Data analysis

As drawing performances on the baseline assessment task and the transfer task were binary coded, we used contingency tables with chi-squared analyses to compare the proportions of students who correctly drew the geometric shapes in these tasks. Analyses of variance (ANOVAs) followed by Tukey post hoc comparisons were used not only to test the effects of study condition on the total angle difference in the students' drawings but also to compare students' ratings of their interest in the task.

Before running ANOVAs, we checked the normality and homogeneity of variance. This assumption was not met for one variable, we therefore used Welch's correction.

In the training phase, for each triangle, we measured the difference between the drawn angles and correct angles, and success in correctly drawing the geometric shape. As students performed these three exercises over time, the independence assumption of the collected data was violated (Field et al., 2012). We therefore calculated linear mixed models that included learning condition and exercise rank as factors and participants as random effects to analyse the data collected in the learning phase, using the lme4 package of R software (Bates et al., 2015). The deviances of nested models were compared using chi-squared tests. As data were binary coded (0 or 1), we applied logistic regression to students' success in drawing the three triangles. Linear regressions were used to analyse angle differences.

RESULTS

The following analyses were not always conducted on the same number of participants. There were some missing values for some analyses, owing to absent or incomplete answers (half-finished triangle in the baseline assessment, transfer task or learning phase) or recording issues (learning phase).

Baseline assessment

As three students did not rate their perceived geometry skills, the ANOVA was conducted on 82 students instead of 85. Results showed no significant differences between the paper-and-pencil ($M=4.19$, $SD=1.21$), tablet without feedback ($M=4.15$, $SD=1.70$) and tablet with feedback ($M=4.61$, $SD=1.60$) groups on students' perceived geometry skills, $F(2, 79)=0.780$, $p=0.462$, $\eta^2=0.019$.

Students were also asked to draw a right-angled triangle to ensure that there were no differences among the three groups on the ability to draw geometric shapes. We compared the proportions of students who successfully performed the task in each of the three groups. Analyses revealed no significant differences among groups, $\chi^2(2)=2.204$, $p=0.332$, Cramer's $V=0.161$, with a very low success level in each one (14.81% for the paper-and-pencil group, 3.57% for the tablet without feedback group and 13.33% for the tablet with feedback group). There were also no significant differences between the paper-and-pencil ($M=36.88$, $SD=42.56$), tablet without feedback ($M=49.64$, $SD=39.99$) and tablet with feedback ($M=39.42$, $SD=46.06$) groups on angle difference, $F(2, 53)=0.478$, $p=0.623$, $\eta^2=0.018$. This baseline assessment showed that students made several errors when drawing triangles, with some reversing the angles or being insufficiently precise when drawing them.

Learning phase outcomes

As stated above, we used linear mixed models including random effects of participants to analyse the data collected in the learning phase. Four models tested the main effects of the independent variables in the present study (learning condition and exercise rank) and the interaction between the two. There was a baseline model with no effects (M0), a model including the main effect of learning condition (M1), a model including the additive effect of learning condition and exercise rank (M2) and a model including the additive effect of learning condition and exercise rank, plus the interaction between these two variables (M3). The deviances of the nested models were compared using chi-squared tests. Based on these comparisons, we selected the most satisfactory model (see Table 3 in Appendix 5).

Task success

Analysis revealed a significant effect of group on students' success in drawing the geometric shapes, $\chi^2(N=249)=51.276$, $p<0.001$. We observed a significant additive effect of exercise rank and learning condition on students' success, $\chi^2(N=249)=20.347$, $p<0.001$. Moreover, results showed a significant interaction between learning condition and exercise rank, $\chi^2(N=249)=24.094$, $p<0.001$.

Consistent with H1, for each exercise, the proportion of students who succeeded in drawing the geometric shapes was higher in the tablet with feedback group than in the other two groups. There was no significant difference between the tablet without feedback and paper-and-pencil groups. Moreover, in the tablet with feedback group, students' performances improved over time (see Figure 1 and Table 1 in Appendix 3 for the percentages of success and the mean scores and standard deviations on angle differences according to learning condition and exercise rank).

Angle differences

Analysis revealed a significant effect of condition on the total difference in the angles drawn by students, $\chi^2(N=249)=14.820$, $p<0.001$. Students in the tablet with feedback group drew geometric shapes with smaller angle differences than those drawn by students in the tablet without feedback group and paper-and-pencil groups, confirming H2 (see Figure 2 in Appendix 3).

Results revealed no significant additive effect of exercise rank, $\chi^2(N=249)=0.275$, $p=0.600$, and no significant interaction effect between group and exercise rank, $\chi^2(N=249)=0.582$, $p=0.900$.

Transfer task

For the transfer task, students were asked to draw two geometric shapes on paper: a geometric shape similar to the one they had practised (near transfer task) and a different geometric shape (far transfer task).

Analysis of the *similar geometric shape* revealed a significant difference among the three groups in terms of success, $\chi^2(2)=9.874$, $p=0.007$, Cramer's $V=0.341$. Consistent with H3a, pairwise comparisons revealed that more students in the tablet with feedback group successfully performed the task than those in the tablet without feedback ($p=0.007$) and paper-and-pencil ($p=0.010$) groups. In the tablet with feedback group, 60% of the students were successful, compared with 25% of students in the tablet without feedback group and 26% in the paper-and-pencil group. Moreover, we analysed if there was a difference among the three groups regarding angle difference for similar geometric shape. Since the assumption of homogeneity of variance was not met for these data, we used the Welch's statistic. Results showed a significant difference among the three groups, Welch's $F(2, 47.155)=4.638$, $p=0.014$, $\eta^2=0.101$. Tukey post hoc analyses indicated that the tablet with feedback group had a smaller angle difference than the tablet without feedback group ($p=0.032$). A marginal difference was also observed between the tablet with feedback group and the paper-and-pencil group ($p=0.059$).

Analysis of the *different geometric shapes* (right-angled triangle) failed to reveal a significant difference among the three groups, meaning that H3b was not confirmed, $\chi^2(2)=1.808$, $p=0.405$ Cramer's $V=0.146$. There was also no significant difference in the angle difference for this geometric shape, $F(2, 73)=0.559$, $p=0.574$, $\eta^2=0.015$.

Interest in the task

Analyses revealed significant differences between students' ratings of their interest in the task, $F(2, 82)=7.300$, $p=0.001$, $\eta^2=0.151$. Consistent with H4, pairwise comparisons using the Tukey test revealed that students in the paper-and-pencil group reported less interest in geometry than students in either the tablet with feedback ($p=0.002$) or tablet without feedback ($p=0.009$) group, see Table 2 in Appendix 4.

DISCUSSION

Theoretical and empirical contributions

Most of the research investigating the use of tablet computers in the classroom have focused on assessing learners' attitudes towards these digital tools, without evaluating how the latter may influence learning outcomes (Haßler et al., 2016). The few studies to have explored the effects of tablet computer use on students' learning have yielded mixed results (Haßler et al., 2016; Nguyen et al., 2015) and have relied on a media comparison approach, without investigating how the tools used (eg, feedback) may differ according to the medium. The present investigation was intended to rigorously assess the effects of using a tablet computer on seventh graders' performances in geometry in a naturalistic environment, by combining a media comparison approach with an added-value approach.

We only expected to observe positive effects on learning in the tablet with feedback group, as the medium per se does not add much for learners when no feedback is provided (Clark, 1983). As hypothesized, results revealed that the proportion of students who successfully drew the geometric shapes during the learning phase was higher in the tablet with feedback group than in the other two groups. Moreover, their performance improved over time. Consequently, results showed that the difference between the drawn angles and the correct ones was smaller for students in the tablet with feedback group than for those in either the tablet without feedback or the paper-and-pencil group. The comparison of the paper-and-pencil and tablet conditions also enabled us to demonstrate that tablet use, which was new to students, did not seem to generate any particular usage difficulties during the learning phase, as performances were similar across the two groups.

One of the most critical results of this study was students' performances on the paper-based transfer task. This task showed that the proportion of students who successfully drew a similar geometric shape (near transfer task) on paper was higher in the tablet with feedback group than in the other two groups. These effects were not observed for the geometric shape they had not practised drawing with provided adaptive real-time feedback (far transfer task), showing that transfer occurred only when the trained procedures were elicited by the transfer task (Geary et al., 2019). The absence of positive effects in the far transfer task could stem from a failure to understand the instructions. The students may not have had the conceptual knowledge of what a right-angled triangle is, even if they had the procedural knowledge needed to draw a right angle.

Consistent with previous literature findings, results also indicated that students in the two tablet groups found the task more interesting than those in the paper-and-pencil group (eg, Mulet et al., 2019; Pruet et al., 2016). This positive effect may have been due to the fact that the novelty of the task medium increased students' motivation (Eutsler et al., 2020; Kaman & Ertem, 2018). Overall, the present study demonstrated that the positive effects observed on students' performances were due not to the medium used, but to the feedback they were given during their drawing activity. This emphasizes the importance of combining a media comparison approach with an added-value approach. Previous investigations had mainly featured a media comparison approach and did not control for the features and possibilities offered by the media themselves. Thus, the effects reported in media comparison studies may have been due either to the medium used or its design features (Herodotou, 2018). It is impossible to conduct a perfect media comparison between paper and pencil and tablet computers, as the technology is always associated with an app that transforms users' interactions. Even if we had aimed to achieve the most similar interactions possible across the paper-and-pencil and tablet computer groups, we would still have had to contend with certain features of the app that are not possible on paper (eg, lines drawn freehand that are automatically recognized as lines and made straight). Consequently, we reasoned that not only changing the medium but also separately testing the features of the new medium itself would allow us to clarify the effects of tablet computers on students' learning in a complementary way. The similar performances of the paper-and-pencil and tablet without feedback groups in our study are consistent with the results of several previous studies (eg, Haßler et al., 2016; Norman & Furnes, 2016) and answer our first objective. The added-value approach allowed us to manipulate just the presence/absence of feedback. We thereby ensured that the positive effects on students' learning were due to the provision of corrective feedback and not to the medium itself, which answered our second objective.

According to Hattie and Timperley's (2007) model, the purpose of feedback is to reduce the gap between learners' current performance and a desired goal. As learners in the tablet with feedback group received coloured feedback, they could easily see and correct their mistakes in order to successfully complete the task. By contrast, the students in the tablet without feedback and paper-and-pencil groups received no information about the correctness or otherwise of their drawing. They therefore had no way of noticing their mistakes and assessing their progress. Moreover, the fact that the students' performance improved over time in the tablet with feedback group indicates that they understood the feedback they received and corrected their geometric shapes accordingly. We believe that using corrective feedback can have positive effects, as students need to actively infer why some angles are correct or not. Moreover, feedback could prove particularly useful for novice learners who need to acquire math skills. As we indicated earlier, one very encouraging result of our study is that students in the feedback group performed much better on the paper transfer task, even though they were no longer receiving any feedback. Therefore, our results show that immediate real-time adaptive feedback was efficient even if it was limited to indicating the correctness of students' responses (ie, knowledge of results, KR; Attali & van der Kleij, 2017; Panadero & Lipnevich, 2022). Moreover, this immediate feedback was not only efficient in the short run while solving the geometric exercises (see Shute, 2008 for a review) but also efficient for a subsequent near-transfer task. To turn students into autonomous learners, guidance should be given to novices, but it should then be gradually tapered as they become more expert/skilled in the relevant area (see guidance fading effect; Paas & van Merriënboer, 2020; van Merriënboer & Kirschner, 2018). AI could be used precisely to taper guidance in educational applications.

Limitations

Our results demonstrate that design choices for educational technologies influence learners' information processing and, in turn, their learning (see also Abrahamson & Abdu, 2020). In other words, and as it has been claimed in other close areas of research (eg, Mayer & Johnson, 2010, for digital game-based learning), we believe that research on the effects of tablets on learning would benefit from the combination of a *media comparison approach* and an *added-value approach* assessing how various features of the software used affect learning outcomes. In the present study, we provided automated corrective feedback in real time, using an AI system. As feedback is considered to be more effective when it is immediate rather than delayed (eg, Dihoff et al., 2004), we might have obtained different results with delayed feedback. Future studies should specifically explore the potential benefits of such delayed guidance, for as in most geometry learning situations, feedback on students' errors is only provided at the end of the drawing task at best, and sometimes several days later. Research is therefore needed to determine the best time to deliver the message (Johnson & Priest, 2014).

As recommended by Haßler and co-workers (2016), a strong internal validity was sought in this study by controlling all the potential confounding variables to ensure a reliable media comparison combined with an added-value comparison. This study also had a good external validity as it was conducted in students' naturalistic environment. Moreover, the geometric exercises were prepared in close collaboration with the students' mathematics teachers and correspond to the kind of exercises they can perform in class. Yet, the external validity could be increased even more by investigating the effects of using this app through several sessions on students' performance (longitudinal study). Furthermore, in the present study, mathematics teachers' feedback was not provided during or after the task. In order to be even more ecological, future studies should also consider this kind of feedback and assess whether it could complement that provided by the application. It could also be argued that the same effects of real-time feedback could be obtained if a teacher followed individual students as they performed the exercise. This condition was not feasible in our study setting but could be included in future studies to verify this assumption.

Another limitation of our study is that we only retained one function of feedback (learning/performance), even though it can also be used to improve motivation and self-regulation of learning (Lipnevich & Panadero, 2021; Panadero & Lipnevich, 2022, for reviews). Moreover, more elaborate feedback could be investigated in order to intensify the positive effects obtained. Instead of using only corrective feedback (KR, allowing students to verify the correctness of their response), it could be possible to provide students with the correct response (knowledge of correct response, KCR) and even to provide them with additional information such as mathematics explanations, strategic prompts or worked-out examples (elaborated feedback; see Attali & van der Kleij, 2017). The AI system composing the geometry app used in the present study could anticipate students' difficulties on the basis of previous exercises and provide them with adaptive guidance just before they reach a problematic step. This kind of sophisticated feedback could prove to be effective, as previous studies have shown that elaborated feedback is more effective than KR and KCR (Attali & van der Kleij, 2017; Van der Kleij et al., 2015).

CONCLUSION

The present study showed that the medium per se does not influence students' performance in geometry. It is important to focus on the features that tablet computers can offer when used in educational settings. These tools allow teachers to use apps designed specifically to promote students' learning. It is impossible for teachers on their own to provide step-by-step feedback to each and every student in their class. However, this becomes possible with technology-enhanced applications (eg, Bonneton-Botté et al., 2019; Van der Kleij et al., 2015). Thanks to AI, these apps can provide students with real-time corrective feedback that shows them their mistakes and encourages them to correct them. By using AI systems such as IntuiGéo, we could assess whether this type of app could be used in the future to provide adaptive guidance in the form of specific or more detailed instructions on the basis of learners' difficulties observed in previous exercises. Based on Hattie's feedback model (2008), it might indeed be particularly relevant to provide not only *feedback* guidance (eg, and/or to success or failure on a specific part of the task), as we did in this study, but also *feedforward* guidance to give students adaptive cues about the next steps to take in the task.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS APPROVAL STATEMENT AND PATIENT CONSENT STATEMENT

The experiment was conducted in accordance with the principles of the Declaration of Helsinki and following the American Psychological Association Ethical Principles of Psychologists and Code of Conduct. An informed consent form was given to children's parents. We obtained written informed parental consent for each child before starting the experiment. All of them agreed to the study conditions described in the consent form and signed it.

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