Routledge
Taylor & Francis Group

Journal of Research on Technology in Education

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ujrt20

Tablet-to-student ratio matters: Learning performance and mental experience of collaborative inquiry

Cixiao Wang & Shufan Yu

To cite this article: Cixiao Wang & Shufan Yu (2021): Tablet-to-student ratio matters: Learning performance and mental experience of collaborative inquiry, Journal of Research on Technology in Education, DOI: 10.1080/15391523.2021.2015018

To link to this article: https://doi.org/10.1080/15391523.2021.2015018

Published online: 10 Dec 2021.

JOURNAL OF RESEARCH ON TECHNOLOGY IN EDUCATION
https://doi.org/10.1080/15391523.2021.2015018

Tablet-to-student ratio matters: Learning performance and mental experience of collaborative inquiry

Cixiao Wang[a] and Shufan Yu[b]

[a]School of Educational Technology, Faculty of Education, Beijing Normal University, Beijing, China; [b]School of Educational Information Technology, Central China Normal University, Wuhan, China

ABSTRACT
The use of virtual manipulatives (VMs) in tablets has become increasingly popular in science courses, and previous studies have indicated its educational benefits. However, the tablet-to-student ratio (TSR), which may affect students' learning, has rarely been examined. This study compares how learning in groups with different TSRs influences the learning performance and mental experience of elementary school students. Participants were 117 fifth-grade students who were randomly assigned to two groups: Group 1:1 (i.e., each student had one tablet) and Group 1:m (i.e., each group shared one tablet) to learn the topic of triboelectrification. The results demonstrated that the students with a 1:m TSR performed better than those with a 1:1 TSR in terms of group work; that students with a 1:m TSR showed a higher degree of involvement during collaborative inquiries; and that the retention test, cognitive load, and group-process satisfaction results showed no significant difference between the two conditions. The findings indicate that the positive effect of collaboration on individuals may gradually disappear and the tradeoff between TSR and time of intervention should be considered during instruction.

ARTICLE HISTORY
Received 16 April 2021
Revised 1 December 2021
Accepted 2 December 2021

KEYWORDS
Mobile learning; virtual manipulative; CSCL; cognitive load; task involvement; inquiry learning

Introduction

In recent years, virtual manipulatives (VMs) have been widely employed in education, as they serve as mediations (e.g., dynamic visualizations, virtual experiments) to support students' scientific inquiry activities by contextualizing them in a simulated interactive environment (e.g., Cai et al., 2020; Kapici et al., 2020; Olympiou & Zacharia, 2012; Wu et al., 2018; Zacharia & Michael, 2016). With the support of informational technologies, VMs provide learners with unique affordances, such as visualizing unobserved experimental phenomena, addressing unanticipated events, minimizing measurement errors, and providing timely feedback (De Jong et al., 2013; Zacharia & Michael, 2016). Previous studies have shown that VM has equal (Kapici et al., 2020) or even superior (Olympiou & Zacharia, 2012) educational benefits compared with other learning materials (e.g., physical manipulatives; PMs) in terms of students' conceptual understanding, especially in the science domain (e.g., Kapici et al., 2020; Olympiou & Zacharia, 2012; Wang et al., 2020b).

Understanding the nature of science is broadly viewed as an essential component of students' scientific literacy (García-Carmona & Acevedo-Díaz, 2018; National Research Council, 2000), in which collaborative inquiry is always deemed one of the best approaches to acquiring scientific knowledge (Bell et al., 2010). In this context, VMs based on portable devices (e.g., tablets, phones,

CONTACT Shufan Yu yushufan1993@gmail.com School of Educational Information Technology, Hubei Research Center for Educational Informationization, Central China Normal University, Wuhan 430079, P. R. China.

and whiteboards) have been increasingly advocated as collaborative inquiry methods in the past few years (Haßler et al., 2016; Kapici et al., 2020), particularly when computer simulation technologies (e.g., AR, VR) become mature and prevalent. While the use of VMs in tablet-supported collaborative scientific inquiry learning (TSCSIL) has already shown its potential, the tradeoff between different affordances of tablets (e.g., resource allocation) and corresponding learning scenarios during the inquiry process remains completely unexplored and urgently needs to be considered (Haßler et al., 2016). With respect to resource allocation in TSCSIL, the tablet-to-student ratio (TSR), which may affect students' learning by influencing peer collaboration and the role of teachers, has rarely been compared and discussed (Haßler et al., 2016). Among previous studies in digital learning environments, findings about the effects of the TSR have been inconsistent. Some studies suggest that a 1:1 TSR (each student had one tablet) could provide seamless acquisition of resources and enhance students' learning performance (Cai et al., 2020; Wong & Looi, 2011). Other empirical studies show that 1:m TSR (each group shared one tablet) is more beneficial to collective output and knowledge acquisition (Lin et al., 2012; Wang et al., 2020b). These mixed results, we argue, might be attributed to the different learning scenarios and students' corresponding mental experience. Moreover, a lack of direct comparison between 1:1 TSR and 1:m TSR in TSCSIL was revealed (Haßler et al., 2016). Therefore, to advance the understanding of the effects of the TSR on students' learning performance and mental experience, further exploration is needed.

In this study, a VM-based TSCSIL lesson was designed for students who are learning the topic of triboelectrification, which is a typical case in Chinese elementary school science curricula. A quasi-experimental study was conducted in an elementary school to explore whether the TSR has an impact on students' learning performance and mental involvement during TSCSIL. Specifically, this study focused on a comparison between two types of TSRs: 1:1 and 1:m. Students' learning performance and mental experience were examined to answer this question.

Literature review

Collaborative scientific inquiry and VM

Science inquiry is an essential component of classroom teaching (National Research Council, 2000). Science inquiry enables students to understand and apply scientific concepts and methods by retrieving information, conducting research, discussing topics and practicing applications (Bell et al., 2010; Tolentino et al., 2009). However, science curricula involve some abstract concepts and complicated knowledge that may exceed students' cognitive abilities and further impair their learning (Kirschner et al., 2018; Liu et al., 2021). According to the theory of group cognition, which posits that knowledge sharing in the context of a community can build group knowledge that surpasses the individual knowledge of group members (Stahl, 2005), researchers emphasize the role of collaboration during science inquiry. Through collaborative inquiry learning (CIL), students can infer scientific principles or solve problems based on active communication and exploration with the assistance of some learning technologies (e.g., computer simulations, virtual labs, and tangible materials) (Bell et al., 2010; De Jong & Van Joolingen, 1998; Lazonder & Harmsen, 2016). Compared to learning by individual, students are able to solve problems more efficiently by collaboratively combining information elements distributed across individuals, thereby forming collectively working memory (Kirschner et al., 2009). In this regard, researchers were actively advocating learning science through CIL (e.g., García-Carmona, 2020; Petersen et al., 2020).

In recent years, with the maturity of new technologies, there has been an upsurge of interest in using interactive, low-cost, and scalable VM on a portable device (e.g., mobile phone, tablet) to support CIL (e.g., Liu et al., 2021). Specifically, with the support of tablets, students can collaborate in inquiry projects by relieving teachers of some of their responsibilities and enabling direct information exchange among them, anytime and anyplace (Bell et al., 2010; Wong & Looi, 2011). In this context, VM has been widely utilized in TSCSIL courses to facilitate hands-on activities when teaching scientific concepts and phenomena (e.g., Cai et al., 2020; Clariana, 2009; Wang & Tseng, 2018).

However, while tablet-based VM provides students with seamless acquisition of resources during CIL (Haßler et al., 2016; Wong & Looi, 2011), the dynamics of the interaction and collaboration mode of students may greatly vary since they would be exposed to different amounts of guidance or support (Kirschner et al., 2018; Lin et al., 2012), which would further influence their learning performance according to group cognition theory (Theiner, 2014). This finding prompted requirements on the tablet-to-student ratios (TSRs), as discussed in the next section.

Tablet-to-student ratios

Since the notion of 1:1 learning (one mobile device per student) has been expounded by Chan et al. (2006), dozens of subsequent studies cited this type of learning and implemented its use (Jong et al., 2020; Looi et al., 2011). Previous research has identified the positive effect of a 1:1 learning setting on students' learning achievement, motivation, and engagement compared to other conditions (e.g., non-tablet condition or other TSR) (Harper & Milman, 2016; Zheng et al., 2016).

However, due to some constraints on the actual teaching situation, such as the availability of suitable content, technological issues concerning the tablet (e.g., network and battery), and the operational troubles of students (Haßler et al., 2016), students' learning performance may greatly vary according to their technological familiarity and abilities. In this regard, much research has promoted the collaborative use of tablets (e.g., Cai et al., 2020; Clariana, 2009; Lin et al., 2012; Liu et al., 2021; Wang et al., 2018). During CIL, the cognitive process would be distributed across the members of a group (Theiner, 2014), through which individual ideas would be systematically aggregated to solve problems. Two modalities of tablet use were subsequently emerging: 1:1 (with collaboration) and 1:m (with collaboration) (Haßler et al., 2016). For the former, advocators posited that individuals in groups can autonomously explore the contents and materials to generate more ideas (Looi et al., 2011; Zheng et al., 2016), thereby promoting their discussion and interaction. However, when each individual owns his or her device, conflicts may arise within groups due to the excessive autonomy that emerged in the 1:1 TSR environment (Lin et al., 2012), which subsequently hinders students in reaching a consensus. As depicted by collaborative cognitive load theory (CLT; Kirschner et al., 2018; Liu et al., 2021), a better learning outcome lies in well-structured problems and effective collaboration. When students have too many conflicts during CIL, collective working memory is hard to form, thereby producing a high extraneous load. In this regard, some studies recommended equipping each group with one tablet (i.e., 1:m TSR) to try to reduce cognitive conflicts and enhance knowledge construction during CIL (Cai et al., 2020; Wang et al., 2018).

Based on the debate about whether 1:1 is better or 1:m is better, researchers have conducted relevant explorations (Clariana, 2009; Lin et al., 2012; Wang et al., 2020b), and mixed results have been obtained. In their 2009 study, Clariana (2009) applied laptops to support students' mathematics learning; the results showed that students in a 1:1 TSR setting performed better than those in a 1:5 TSR setting. On the other hand, in Lin et al.'s (2012) work, two modalities of tablet use (i.e., 1:1 & 1:m) in collaboration with concept mapping were compared. Different from Clariana's (2009) finding, students with a 1:m TSR performed better than those with a 1:1 TSR in terms of concept map score. However, due to relatively less autonomy than those in the 1:1 group, they demonstrated relatively worse quality interactions. Moreover, in our previous work (Wang et al., 2020b), a preliminary comparison among different TSRs on the topic of lever was conducted. Students in the 1:m condition presented a better group worksheet result and flow state and similar retention test results and cognitive load levels compared to the 1:1 group. Similarly, nonsignificant results on learning gains between the 1:1 condition and the 1:m condition were obtained in Liu et al. (2021)'s work.

However, as depicted by Haßler et al. (2016), studies that compare different TSRs are still too rare to synthesize reliable findings to support educational practice, let alone consider the impact of TSR on collaborative performance during learning and post-hoc individual performance during testing at the same time. What is more, while the benefits of TSCSIL were mentioned by previous studies, the subsequent influence on individual performance was rarely discussed. Although a pioneer work of Kirschner et al. (2009) explored the effects of using tablets with or without collaboration on individuals' learning performance and the results confirmed the positive effect of collaboration, the collaborative performance which would directly reflect the group work efficacy were ignored.

Based on the abovementioned considerations, more details on how students' learning varies with different TSRs are needed. This study triboelectrified the empirical evidence by comparing students' learning performance (collaborative performance during learning phase and individual performance during testing phase) and mental experience through another scientific topic—triboelectrification.

Mental experience during collaboration

According to the former reviewed findings, during face-to-face collaboration, the cognitive load (CL) may arise among students when they face too many conflicts deriving from different TSRs (Kirschner et al., 2018; Wang et al., 2020b). In this case, to understand the underlying reason, it is necessary to introduce CL theory (CLT) to provide further explanation. In general, CLT asserts that learning is constrained by limited working memory capacity (Paas & Van Merriënboer, 1994), and CL (Kirschner et al., 2018) refers to the sum of the working memory resources required to perform a learning task. During collaborative learning, multiple working memories collaborate on the same task or problem (Kirschner et al., 2018), and collective working memory can then be created through communication and collaboration, thus generating a better collective knowledge structure. Furthermore, various interactive elements can be distributed among the working memories of other group members, which will reduce the CL on single working memory (Kirschner et al., 2018). However, when group members have difficulties exchanging knowledge and information due to improper tasks or instructional designs, the collective working memory of the group will not be easy to form and thus may further impair students' learning performance and CL (Kirschner et al., 2018; van Merriënboer & Sweller, 2005).

Based on these considerations, when adopting VM-based TSCSIL, different modalities of tablet use may affect the information exchange and task coordination in the process of cooperation, with different CL results within individuals (Kirschner et al., 2018; Wang et al., 2020b). For instance, whether team members could share the same working interface determines how much effort is needed for information exchange. However, studies that compare the impact of different TSRs on learners' CL are rare. Thus, it is necessary to further explore the CL levels of learners with different TSRs. As an important measurement of CL in multimedia learning (Mutlu-Bayraktar et al., 2019), the assessment factors mainly consist of mental load (ML) and mental effort (ME) (Paas & Van Merriënboer, 1994). ML derives from the number and degree of information interactions between a task and a subject, while ME relates to formats and manners of information presentation and teaching strategies (Paas & Van Merriënboer, 1994). This study attempted to measure CL from these two dimensions.

Furthermore, based on the assessment factors of CCT (Paas & Van Merriënboer, 1994), Paas et al. (2005) proposed an ME performance coordinate system and a formula to compute the task involvement of students in cognitive tasks. According to Paas et al. (2005), the calculation and representation of student-related involvement in instructional conditions can enhance research on the effectiveness of complex cognitive tasks (Wang et al., 2020b). In addition, satisfaction with digital artifacts, which describe how pleasant learners perceive learning activities, also serves as an important measuring factor for evaluating students' learning effectiveness (e.g., Cai et al., 2020; Wu et al., 2018). During tablet-supported group collaboration, the different learning processes mediated by different modalities of technological support will dictate team member information exchange patterns, which also subsequently impact group-process satisfaction (Andres, 2006). However, while previous studies examined satisfaction with the VM-supported learning environment, most studies focused on the learning materials rather than interpersonal factors (e.g., Cai et al., 2020; Wu et al., 2018). Therefore, the group-process satisfaction scale proposed by (Savicki et al., 1996) was utilized in our study to investigate the extent to which a student is satisfied with the collaboration of his or her group.

To summarize, when investigating students' mental experience in different learning situations, how students' learning engagement and satisfaction vary is worth exploring. Therefore, in this study, CL, task involvement, and group-process satisfaction were involved in evaluating students' mental experience during collaborative inquiry learning.

Purposes of this study

Based on the aforementioned theoretical background and empirical studies, we assume that TSRs could influence inquiry performance during collaborative inquiry learning. Specifically, this study considered two modalities of using VM based on tablets: 1:1 TSR and 1:m TSR. A 1:1 TSR means that each student in a group has a tablet, while a 1:m TSR indicates that each group shared one tablet. The main purpose of this study is to compare learning performance and mental experience for different TSRs. To address this issue, we conducted a quasi-experiment in an elementary school. Two research questions are posed:

1. What are the differences in learning performance (i.e., collaborative performance during learning and individual performance during testing) between 1:1 TSR and 1:m TSR in collaborative inquiry learning?
2. What are the differences in mental experience (i.e., cognitive load, task involvement, and group-process satisfaction) between 1:1 TSR and 1:m TSR in collaborative inquiry learning?

Experimental design

Inquiry materials

Triboelectrification, the topic that depicts the phenomenon that two samples of the same materials may charge each other when they are rubbed together (Lowell & Truscott, 1986), is an important knowledge point in Chinese elementary school science curriculums. Given that the transfer of the electric charge caused by friction is difficult to observe in real life, students could not gain a deep understanding of this abstract concept. Thus, based on this topic, we selected the simulation tool "Balloons and Static Electricity" (Balloons and Static Electricity, 2021) from the PhET learning platform as the learning material. This virtual triboelectrification manipulative (VTM) illustrates the phenomenon of triboelectrification by visualizing the transfer of the electric charge generated in the friction between the balloon and the sweater. As shown in Figure 1, the inquiry materials contain some interactive elements (e.g., balloons, sweater, and wall), which aim to support students' hands-on activities. Specifically, students can select one or two balloons to rub against a sweater by finger-screen haptic interaction. The transfer of charges would be visualized in real time, with the movement of balloons. Learners were required to learn the triboelectrification phenomenon by observing the charge interaction (i.e., similar charges repel, dissimilar charges attract) through CIL.

According to Lazonder & Harmsen, (2016), adequate guidance should be employed to assist students in accomplishing tasks during inquiry learning. We offered a group worksheet to proceed with the inquiry learning step by step, which will be mentioned in subsequent sections.

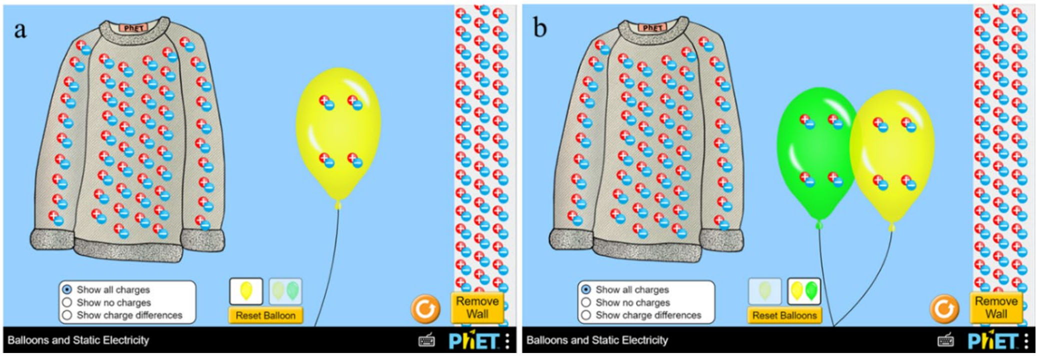

Figure 1. Interfaces of virtual triboelectrification manipulative.

Participants and experimental procedure

The participants of this study were 117 fifth-grade students (aged 11 on average) from four classes of a public elementary school in Beijing, China. The participants were randomly divided into Group 1:1 (26 boys and 33 girls) and Group 1:m (27 boys and 31 girls). Table 1 shows the information of group compositions for the two groups, including group size, number of males in a group, and number of females in a group. The chi-square tests showed that the number of students in a group (group size) has no significant difference between group 1:1 and 1:m (χ^2 = 1.477, $p = 0.688 > 0.05$) and there was no significant difference on the gender distribution between the two groups (number of male: χ^2 = 4.400, $p = 0.355 > 0.05$; number of female: χ^2 = 2.752, $p = 0.253 > 0.05$), indicating the two conditions had similar group compositions.

These students had not learned the knowledge of triboelectrification before treatment and were taught by the same science teacher with a teaching experience of 10 years. The experiment was conducted across three weeks in September 2019, which marked the beginning of the new semester.

Note that in the last semester before treatment, students have already been taught some prior knowledge that may be helpful for learning triboelectrification based on tablets, such as the simple circuit and electromagnetic induction. At the end of the last semester, 116 of the 117 students participated in the final exam (a girl was absent from the final exam and she was randomly assigned to the 1:m group). The content of the exam is about the learning theme of the last academic year, including the knowledge points of simple circuits, electromagnetic induction, and light refraction, etc. According to the exam scores of the last academic year (the total score was 100), there was no significant difference (t (114) = −.313, p = .151 > .05) between group 1:1 (Mean = 81.46, SD = 8.02) and Group 1:m (Mean = 81.04, SD = 6.42). This indicates that the students in the two groups had a similar level of academic performance in the science subject or prior knowledge level in the learning topic of triboelectrification. In addition, considering that the treatment was carried out at the beginning of the new semester (i.e., September) and that the same batch of tablets (Android system, 8-inch screen) was utilized in this

Table 1. Chi-square tests of group compositions.

Group size	2	4	5	6	χ^2	*N*	χ^2	*p*
1:m	1	2	6	3		12	1.477	0.688
1:1	0	3	7	2		12		
Number of Male in a group	1	2	3	4	5	*N*	χ^2	*p*
1:m	1	5	4	2	0	12	4.400	0.355
1:1	0	5	6	0	1	12	χ^2	χ^2
Number of Female in a group	0	2	3	χ^2	χ^2	*N*	χ^2	*p*
1:m	2	3	7			12	2.752	0.253
1:1	1	7	4	χ^2	χ^2	12	χ^2	χ^2

experiment, we assumed that the two groups (i.e., Group 1:m and Group 1:1) had similar starting points both for the tablet using experience.

According to Pedaste et al. (2015), the core phases of the inquiry cycle include 5 stages: (1) *orientation*, (2) *conceptualization*, (3) *investigation*, (4) *conclusion*, and (5) *discussion*. This cycle highlights the key features of scientific thinking and has become guidance for some later works (e.g., Petersen et al., 2020). Therefore, the CIL activities of this study were designed followed by Pedaste et al.'s (2015) inquiry phases. Refer to Figure 2. The detailed experimental procedure and its corresponding inquiry phase are described as follows:

The experiment in the first week consisted of two stages: introduction, randomization (20 min), and basic knowledge teaching (40 min). At the initial stage, students in each group were randomly divided into 12 subgroups, with approximately 4–6 students in each subgroup. The science teacher then briefly introduced the learning topic (triboelectrification) and left students work concerning identifying the triboelectrification phenomenon in daily life. This task partly corresponded to the *orientation* phase, as the learning topic was briefly introduced. One day later, the second phase, class teaching, was conducted to introduce the basic knowledge of triboelectrification; for example, students were required to collaborate in some designated face-to-face activities (e.g., rub a ruler against hair to attract small pieces of paper) to make the triboelectrification phenomenon register in their brain. In this context, some issues emerged, e.g., what caused this phenomenon? This part was consistent with the *orientation* and *conceptualization* phase since the topic and the problem were introduced.

One week later, knowledge was further imparted through VM-based TSCSIL. The inquiry activity includes two parts: the introduction of inquiry activity (10 min) and the collaborative

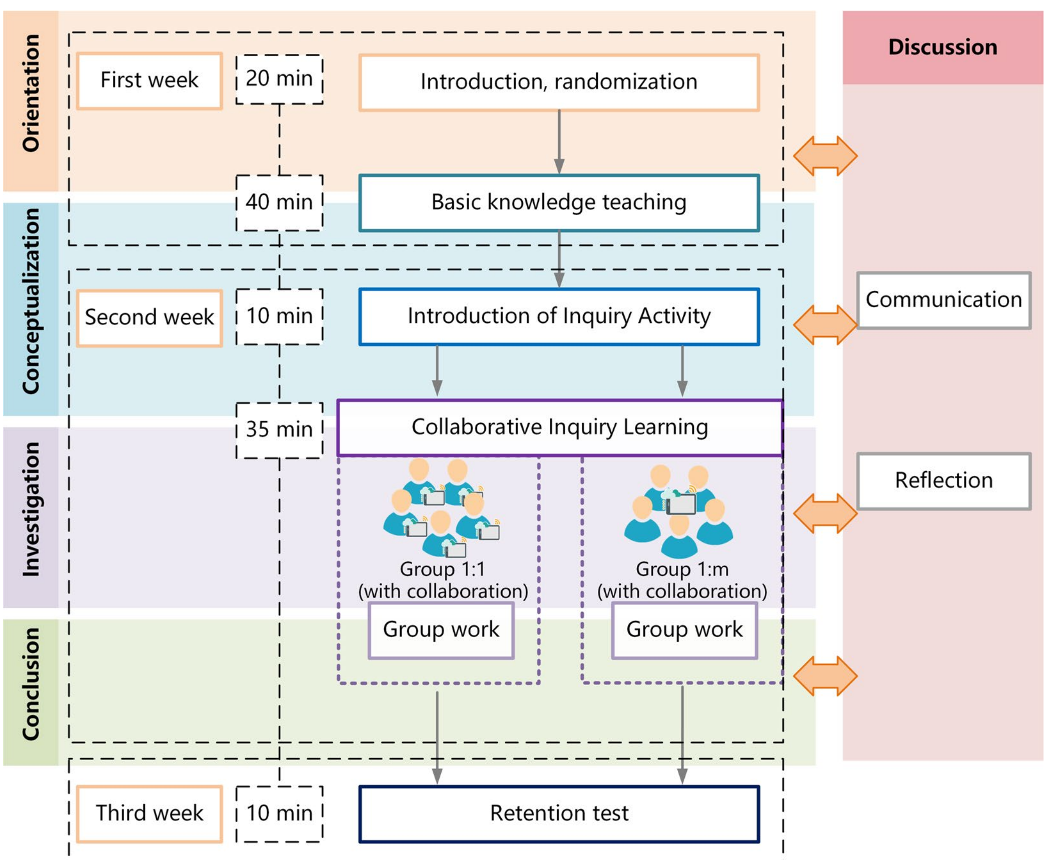

Figure 2. Diagram of experiment procedure and its connections to inquiry phases.

inquiry learning process (35 min). The first part was introduced by the science teacher and corresponded to the *conceptualization* phase, as students were informed of some issues to which they needed to pay attention during the activity. The second part, collaborative inquiry learning, was conducted by groups with the guidance of a group worksheet in paper form. Each sub-group was administered with one group worksheet, and students should cooperatively finish the group worksheet by operating the VTM with one tablet per group (Group 1:m) or one tablet per person (Group 1:1). The class collaborative learning scenarios of two representative learning groups are shown in Figure 3. After the learning activity, we administered several questionnaires to examine students' CL, group-process satisfaction, and task involvement. This part drew upon elements of the *investigation* and *conclusion* phase, as the students were involved in exploring the issues and synthesizing their findings.

Note that, among all the phases, the students were required to collaborate in communicating their findings and conclusions to others, as well as reflecting issues during their TSCSIL.

In the last week, a knowledge retention test (10 min) was conducted to investigate students' individual performance.

Instruments

Assessment tools

To perform a comprehensive examination of students' learning performance, we designed two assessment tools: a *group worksheet* to guide the CIL and assess students' task performance of the inquiry activity (i.e., collaborative performance) and a *Retention test* that aimed to evaluate students' knowledge retention concerning triboelectrification (i.e., individual performance).

Group worksheet. As shown in Appendix A, according to the different contexts of VTM (refer to Figure 1a and b), two learning tasks were presented on the group worksheet with scores of 50 points each. Each task consisted of three questions or guidance to facilitate their step-by-step inquiry, e.g., *"Rub the yellow balloon against the sweater and observe the change in the balloon and sweater. Do positive and negative charges move? How did they move?"*

Retention test. This retention knowledge test consists of one fill-in-the-blank question (i.e., *"The essence of triboelectricity is the transfer of __"*), one true or false question (i.e., *"Rub the balloon with the sweater; only the negative charge will move"*), and four multiple-choice questions (e.g., *"In the experiment of triboelectrification, which description is wrong: A. After the balloon rubs against the sweater, the sweater becomes positively charged; B. After the balloon rubs against the*

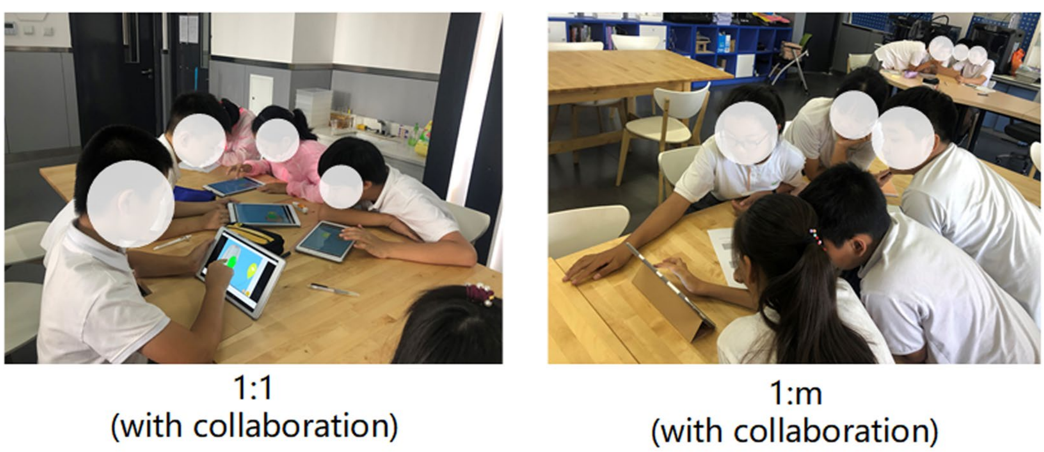

Figure 3. Collaborative situations.

sweater, the balloon becomes negatively charged; C. The rubbed balloon attracts the sweater; D. The rubbed balloon repels the sweater") with a total score of 60 (i.e., 10 points for each item).

All questions in the retention test and group worksheet were jointly developed by the science teacher and researchers following the science curriculum syllabus. Furthermore, another teacher with more than ten years of teaching experience and an expert in science education were consulted to recheck these questions.

Questionnaire

The questionnaire distributed after the collaborative inquiry learning activity contains a cognitive load scale and a group-process satisfaction scale (refer to Appendix B). To better understand the group process in different conditions, we also designed open questions to collect qualitative data of how students collaborate through tablet(s) and the difficulties they encountered during collaboration. The CL scale consists of the ML dimension and ME dimension with four items, which were based on the measures proposed by Paas & Van Merriënboer (1994) and adapted from the research of Hwang et al. (2013). The group-process satisfaction (GS) scale, which aimed to investigate the extent that a student is satisfied with the collaboration of his or her group, was adapted from the scale developed by Savicki et al. (1996) and has four items in total. All items of the scales are rated on a seven-point Likert scale. Cronbach's alpha coefficients for the ML scale, ME scale, and GS scale were .941, .810, and .900, respectively, suggesting high reliability in internal consistency.

Results

Learning performance

The learning performance was reflected by the group worksheet (group level) and retention test (individual level).

The group worksheet was collaboratively finished by students in each sub-group of two conditions. Since the groups showed similar composition according to the abovementioned chi-square test result, we compared the data on group level. Shapiro-Wilk test was firstly utilized to check the normality of the data. The results showed each group was normally distributed (group 1:m: $p = .216 > .05$; group 1:1: $p = .495 > .05$). As such, an independent sample *t*-test was subsequently performed to compare the difference in students' learning performance in terms of the group worksheet score under the impact of the TSR. As shown in Table 2, a significant difference was found between group 1:m and 1:1 (t (24) = 2.364, p =.027 < .05, Cohen's $d = 0.96$). Specifically, students in group 1:m (Mean = 81.25) performed better than those in group 1:1 (Mean = 71.25) in terms of their collaborative work (Mean difference = 10).

An independent sample *t*-test was conducted to further compare the knowledge retention of individuals. The result showed students in both groups retained similar knowledge on the topic of triboelectrification one week later (t (115) = 0.768., p =.444) (see Table 2). In addition, we found the test results were only slightly higher than half of the total score 60 (group 1:1: Mean = 35.17, group 1:m: Mean = 33.05).

To sum up, these findings indicate that the students in Group 1:m performed significantly better than the students in Group 1:1 in collaborative inquiry tasks and that the two groups had a similar knowledge retention one week later.

Table 2. Independent sample *t*-test for the comparison of learning performance of each group in different stages.

	1:m			1:1					
Learning performance	*N*	Mean	S.D.	*N*	Mean	S.D.	*t*	*df*	*p*
Group worksheet score	12	81.25	8.292	12	71.25	12.084	2.364*	22	0.027
Retention test score	58	35.17	14.539	59	33.05	15.341	0.768	115	0.444

Note. * $p < .05$.

Cognitive load and group-process satisfaction

In this study, we applied scales to investigate students' CL and GS for different tablet-to-student ratios when using VM. The mean and standard deviation values of the ML, ME, and GS of students are shown in Table 3. An independent-sample t-test was utilized for the data analysis. As shown in Table 3, there was no significant difference in ML (Mean Difference = 0.154, $t(115) = 0.511$, $p = .610 > .05$), ME (Mean Difference = −0.092, $t(115) = -0.293$, $p = .770 > .05$), or GS (Mean Difference = −0.050, $t(115) = 0.170$, $p = .865 > .05$) between the two groups.

Task involvement

In this study, we adopted the task involvement formula proposed by Paas and his associates (2005) to calculate task involvement during collaborative inquiry learning. In the following formula, I refers to the task involvement (I) of students, R represents the z-score for ME, and P represents the z-score for performance.

$$I = \frac{R + P}{\sqrt{2}}$$

Specifically, scores of group worksheets were applied to represent students' performance on inquiry tasks. By subtracting the total mean from each score and then dividing the result by the total standard deviation, the students' scores for ME and performance were standardized. The mean and standard deviation values of students' task involvement are shown in Table 4. An independent-sample t-test was performed to compare the difference in students' task involvement between the two groups. The result shows that the students in Group 1:m had significantly higher task involvement in group work than the students in Group 1:1 (Mean Difference = 0.602, $t(109.214) = 3.469$, $p < .001$, Cohen's $d = 0.64$).

Moreover, the motivational effects of instructional conditions can be visualized by the ME-Performance coordinate system (Paas et al. 2005). As shown in Figure 4, each point in this coordinate system represents the ME Z-score and related performance Z-score of a student involved in this study. A point above the diagonal means that the corresponding student had relatively high involvement ($I > 0$), and a point below the diagonal refers to relatively low involvement ($I > 0$). The percentage of students in Group 1:m who had relatively high involvement ($I > 0$) was 65.52% ($n = 38$), while 47.46% ($n = 28$) of the students in Group 1:1 showed a higher level ($I > 0$) of task involvement. The chi-square test showed that the students in the two groups had different task involvement levels ($\chi^2 = 3.879$, $p = .049 < .05$). These findings also indicate that students with a 1:m TSR experienced higher involvement during the collaborative task, while students with a 1:1 TSR had relatively low involvement.

Table 3. Descriptive analysis of cognitive load and group-pross satisfaction.

	Group	*N*	Mean	S.D.	*t*	*df*	*p*
ML	1:m	58	3.086	1.582	0.511	115	.610
	1:1	59	2.932	1.676			
ME	1:m	58	4.065	1.607	−0.293	115	.770
	1:1	59	4.156	1.791			
GS	1:m	58	5.698	1.613	0.170	115	.865
	1:1	59	5.648	1.563			

Table 4. Descriptive analysis of task involvement.

	Group	*N*	Mean	S.D.	*t*	*df*	*p*
I	1:m	58	.304	.816	3.469***	109.214	.001
	1:1	59	−.299	1.050			

Note. *** $p < .001$.

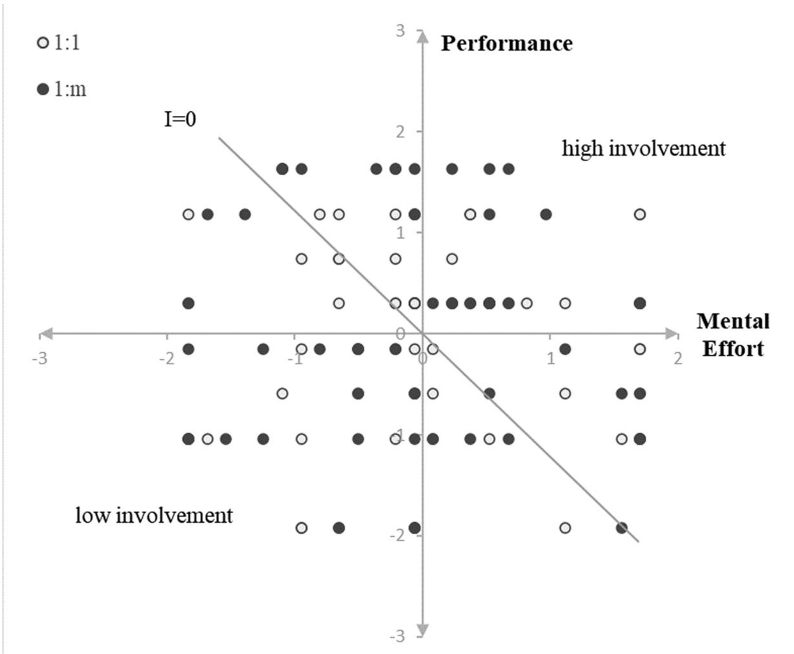

Figure 4. Task involvement of students.

Discussion

This paper aims to examine the influence of different TSRs on students' learning performance and mental experience during VM-based TSCSIL. Two groups with different TSRs (1:m and 1:1) were established in our study. Students were asked to learn triboelectrification, an important topic of the elementary school science curriculum, via the VTM. The learning performance (collaborative performance and individual performance) and mental experience (cognitive load, group-process satisfaction, and task involvement) were concurrently examined. The findings are discussed in the next section.

TSR to learning performance

In general, the results showed that the students in Group 1:m presented a better group work performance but a similar retention test score (individual performance) compared to those in Group 1:1. This finding may indicate that groups sharing one tablet outperformed groups in which each student owned one device in terms of collaborative efficacy. One possible reason is that the students in Group 1:m could only view one screen and that the assigned group work gave more chances for interaction with other students instead of solely paying attention to their own interface, as observed for those in Group 1:1. Accordingly, the cognitive process can be more effectively distributed across the members in a community, leading to better collaborative efficiency (Theiner, 2014). In addition, as depicted by Lin et al. (2012), students in the 1:m groups were less likely to interfere with each other. In our study, we further collected text data related to students' perceptions of the group process with open questions. For instance, we could simultaneously analyze the experimental data and spent more time on the problem-solving task, while only two students dominated the manipulation of the VM, as stated by a student from Group 1:1. In contrast, Group 1:1 would spend more time than Group 1:m to reach a consensus when completing the inquiry topics, which yields unsatisfactory results for group worksheet performance. For example, some students in Group 1:1 indicated that the opinions of group members were often not unified, which caused them to spend too much time checking the manipulation stage with each other. This finding also corroborated the findings of Liu et al. (2021), which revealed that students who shared one tablet allocated a greater frequency of attention to VMs than those who had individual devices in groups. However, the findings contradicted the finding of (Lin et al., 2012) but echoed the findings of (Kirschner et al., 2009) and our previous work (Wang et al., 2020b), implying that the group working of TSRs should be contextualized to specific learning scenarios according to the real situation.

Regarding the results of the knowledge retention test on individual level, Group 1:m showed a slightly higher but nonsignificant result than Group 1:1. This interesting finding implies that no matter under what types of TSR, the positive effect of the collaboration on individuals may gradually disappear within a time. On one hand, this corresponds to Ebbinghaus's forgetting curve (Ebbinghaus, 2013), on the other hand, this may also indicate the positive effect of collaboration on group level are hard to last in the current context. This finding was contradictory to some former studies (e.g., Kirschner, 2009, Wang et al. 2020a). Specifically, The "faded effect" was more obvious in group 1:m. Although the two stages (learning phase and testing phase) cannot be directly compared, the dropped mean correct rate (from 81% to 59%) can to some extend explain, which is much larger than group 1:1 (from 71% to 55%). The phenomena may be attributed to the limited number of devices in a community, which would afford the members fewer opportunities for hands-on operation, thereby distributing uneven attention to the VTM on a screen. In this context, students may not receive a deep understanding of the learning material and may retain relatively less knowledge than obtained via their collaborative performance. In addition, the video recordings revealed that a few students in Group 1:m were reluctant to share their screen with other group members, which may constrain the effect of collaboration on individuals (Haßler et al., 2016). Therefore, although they can easily achieve consistency by short time coordination, the real influence on individuals in groups may be shallow, as they did not have chances as the members in group 1:1, who gave more attention to checking the inter-group inconsistent opinions through self-inquiry via the VTM. This finding contradicted the findings of our previous study, which indicated that students in the 1:m condition performed better than those in the 1:1 condition in terms of the retention test (Wang et al., 2020b). As the given time is reduced, some individuals in groups do not have enough opportunities to access VTM and discussion, thus impairing their knowledge construction.

TSR to mental experience

In this study, we mainly assessed students' CL, GS, and task involvement to reflect their mental experience. In terms of the CL, there was no significant difference between Group 1:1 and Group 1:m in either the ML or ME. This finding revealed that students in both groups shared the learning materials with the same complexity, and the amount of their mental resources that were actually allocated to the learning task was similar (Paas & Van Merriënboer, 1994). This finding corroborates some previous findings, which demonstrated that there is no difference in CL among students with different TSRs (Liu et al., 2021; Wang et al., 2020b). Furthermore, the relatively low results of CL (i.e., lower than 4) also proved the benefits of CIL; that is, the complexity of the to-be-learned material was effectively distributed among group members (Kirschner et al., 2018). The nonsignificant results for GS indicated that the extent to which a student is satisfied with the collaboration of his or her group is similar among students in two groups with different TSRs (Savicki et al., 1996). According to students' text data for open questions, a 1:1 TSR gave students more autonomous rights in operation, while the group had to spend more time on "whether we are together". In contrast, in the 1:1 TSR groups, "All of us could have the same inquiry stage to refer to", even though "only two people control the VTM". The balance problem between individual control and group shared space may lead to no significant difference in GS between the two groups. In general, the low level of ML and ME and the high level of GS (i.e., higher than 5.5) indicated that most students in these two groups had a relatively positive mental experience during the learning activity. This result also affirmed the positive effect of VTM on students' learning experience and aligned with the results of some previous studies (e.g., Turan et al., 2018; Wang et al., 2020b).

Regarding task involvement, students in Group 1:m showed a significantly higher score than those in Group 1:1, which implies that students in groups sharing one tablet had a higher motivation to involve the TSCSIL than those who individually owned devices. This finding echoes the finding of Liu et al. (2021) and Wang et al. (2020b), suggesting that learning involvement must be considered when examining the effects of different TSRs. Moreover, the results reaffirmed the applicability of the computational method proposed by Paas et al. (2005) to compare learners' involvement in TSCSIL activities.

To summarize, unlike our previous work, which focused on the topic of levers, this paper extended the empirical evidence to another topic, triboelectrification. The following findings emerged: regarding the impact of TSRs, the collaborative use of tablets seems better for group work, but in terms of individual knowledge acquisition, it is necessary to dialectically consider the setting of TSRs based on actual teaching needs. In addition, the nonsignificant but positive results on CL and GS reaffirmed the educational benefits of VTM.

Conclusions

This study tried to find out under what TSR students could have a better learning performance and mental experience (i.e., CL, GS, and task involvement). 117 fifth grade students were randomly assigned in two groups with different TSRs (i.e., 1:1 and1:m) and CIL activities were designed based on the inquiry phases proposed by Pedaste et al. (2015). From the empirical results, the following conclusions can be drawn: First, the TSR will affect students' learning performance and task involvement during collaborative inquiry learning. Concretely, in terms of the group worksheet, students with 1:m TSR performed better than those in 1:1 groups; 1:m groups also showed a higher degree of involvement during the collaborative inquiry. However, with respect to the knowledge retention test (individual performance), students with different TSR showed similar results. Second, there was no significant difference between different TSR groups on ML, ME, and GS; more specifically, no matter what group the students were in, they all showed a low level of CL and a high level of GS, indicating VM-based TSCSIL has a positive impact on students' learning experience.

Based on the findings of the current study, some implications for educational practitioners can be highlighted. As for the positive results on CL and GS found among students using VM, more practical applications of VM are suggested to be implemented in education, especially in the science discipline wherein hands-on experiments are needed to construct and consolidate learners' knowledge. Regarding the group worksheet results, we argue that teachers need to consider the design of TSR in combination with specific learning tasks. The TSR of 1:m may be more effective in some classroom teaching situations, as it could afford a shared learning space which is helpful for groups to concentrate more on collective tasks. Moreover, the similar results on individual retained knowledge indicated the positive effects of shared-screen collaborated work may be decreased over time, which put forward requirements on the time of intervention when considering the design of TSR. Additionally, to avoid the shallow effect on students' retention knowledge, the VM application, if possible, can provide to students after school so that they can consolidate knowledge by themselves by running it on their own or their parents' devices.

Some limitations should also be mentioned. First, the collaborative inquiry time (35 min) seems a bit short, which may lead to some unexpected results. For instance, the non-significant results of GS in our study were different from our expectation. For a more convincing result, the time allocation should be taken into consideration. Second, we did not strictly control the "m" in the "1:m", which may influence the efficiency of inquiry learning. Third, we only recorded video in two groups of 1:m condition, which impeded the intention to do a video analysis to enhance the validity of quantitative results. Fortunately, we collected some qualitative evidence through open-ended questions. Some recommendations for future works can be drawn. First, as studies concerning the impact of different TSR on students' learning process remain rare, subsequent research is needed to investigate whether the finding of the current study can be replicated in other disciplines or experiments as well as students in different learning stages (e.g., elementary school students, high school students, and university students). Second, the impact of different group sizes on 1:m VM-based learning is recommended to be investigated in future works. Third, we recommended conducting a video analysis if conditions permitted, since this may produce some valued findings from the qualitative perspective. Forth, learner autonomy, a possible factor that influences the TSCSIL, is also worth exploring in future work. Finally, since individuals are nested in groups, we intend to collective large group data to conduct a multilevel analysis to discover more interesting findings in future studies.

Declaration of conflicting interests

There is no conflict of interest in this study.

Funding

This work was supported by the Fundamental Research Funds for the Central Universities under Grant [number 2020NTSS04] and [number 2020YBZZ037]; and Wuhan Pre funded science and technology project [number 2020010601012190].

Notes on contributors

Cixiao Wang is a lecture at the School of Educational Technology at Beijing Normal University. Her research interests include mobile learning, distance education, and embodied cognition.

Shufan Yu is a Ph.D. student at the School of Educational Information Technology at Central China Normal University. His research interests include Augmented/Virtual Reality in education, virtual manipulatives, and human-computer interactive technology.

References

Andres, H. P. (2006). The impact of communication medium on virtual team group process. *Information Resources Management Journal*, *19*(2), 1–17. https://doi.org/10.4018/irmj.2006040101

Balloons and Static Electricity. (2021). https://phet.colorado.edu/sims/html/balloons-and-static-electricity/latest/balloons-and-static-electricity_en.html

Bell, T., Urhahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: Models, tools, and challenges. *International Journal of Science Education*, *32*(3), 349–377. https://doi.org/10.1080/09500690802582241

Cai, S., Liu, E., Shen, Y., Liu, C., Li, S., & Shen, Y. (2020). Probability learning in mathematics using augmented reality: Impact on student's learning gains and attitudes. *Interactive Learning Environments*, *28*(5), 560–573. https://doi.org/10.1080/10494820.2019.1696839

Chan, T.-W., Roschelle, J., Hsi, S., Kinshuk, Sharples, M., Brown, T., Patton, C., Cherniavsky, J., Pea, R., & Norris, C. (2006). One-to-one technology-enhanced learning: An opportunity for global research collaboration. *Research and Practice in Technology Enhanced Learning*, *1*(1), 3–29. https://doi.org/10.1142/S1793206806000032

Clariana, R. (2009). Ubiquitous wireless laptops in upper elementary mathematics. *Journal of Computers in Mathematics and Science Teaching*, *28*(1), 5–21. https://www.learntechlib.org/p/27026

Council, N. R. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. The National Academies Press. https://doi.org/10.17226/9596

De Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science (New York, N.Y.)*, *340*(6130), 305–308. https://doi.org/10.1126/science.1230579

De Jong, T., & Van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, *68*(2), 179–201. https://doi.org/10.3102/00346543068002179

Ebbinghaus, H. (2013). Memory: A contribution to experimental psychology. *Annals of Neurosciences*, *20*(4), 155–156. https://doi.org/10.5214/ans.0972.7531.200408

García-Carmona, A. (2020). From inquiry-based science education to the approach based on scientific practices: A critical analysis and suggestions for science teaching. *Science & Education*, *29*(2), 443–463. https://doi.org/10.1007/s11191-020-00108-8

García-Carmona, A., & Acevedo-Díaz, J. A. (2018). The nature of scientific practice and science education: Rationale of a aet of essential pedagogical principles. *Science & Education*, *27*(5–6), 435–455. https://doi.org/10.1007/s11191-018-9984-9

Harper, B., & Milman, N. B. (2016). One-to-one technology in K-12 classrooms: A review of the literature from 2004 through 2014. *Journal of Research on Technology in Education*, *48*(2), 129–142. https://doi.org/10.1080/15391523.2016.1146564

Haßler, B., Major, L., & Hennessy, S. (2016). Tablet use in schools: A critical review of the evidence for learning outcomes. *Journal of Computer Assisted Learning*, *32*(2), 139–156. https://doi.org/10.1111/jcal.12123

Hwang, G. J., Yang, L. H., & Wang, S. Y. (2013). A concept map-embedded educational computer game for improving students' learning performance in natural science courses. *Computers & Education*, *69*, 121–130. https://doi.org/10.1016/j.compedu.2013.07.008

Jong, M. S. Y., Tsai, C. C., Xie, H., & Kwan, K., & Wong, F. (2020). Integrating interactive learner-immersed video-based virtual reality into learning and teaching of physical geography. *British Journal of Educational Technology*, *51*(6), 2064–2078. https://doi.org/10.1111/bjet.12947

Kapici, H. O., Akcay, H., & de Jong, T. (2020). How do different laboratory environments influence students' attitudes toward science courses and laboratories? *Journal of Research on Technology in Education*, *52*(4), 534–549. https://doi.org/10.1080/15391523.2020.1750075

Kirschner, F., Paas, F., & Kirschner, P. A. (2009). Individual and group-based learning from complex cognitive tasks: Effects on retention and transfer efficiency. *Computers in Human Behavior*, *25*(2), 306–314. https://doi.org/10.1016/j.chb.2008.12.008

Kirschner, P. A., Sweller, J., Kirschner, F., & Zambrano R, J. (2018). From cognitive load theory to collaborative cognitive load theory. *International Journal of Computer-Supported Collaborative Learning*, *13*(2), 213–233. https://doi.org/10.1007/s11412-018-9277-y

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research*, *86*(3), 681–718. https://doi.org/10.3102/0034654315627366

Lin, C. P., Wong, L. H., & Shao, Y. J. (2012). Comparison of 1:1 And 1:M CSCL environment for collaborative concept mapping. *Journal of Computer Assisted Learning*, *28*(2), 99–113. https://doi.org/10.1111/j.1365-2729.2011.00421.x

Liu, C. C., Hsieh, I. C., Wen, C. T., Chang, M. H., Fan Chiang, S. H., Tsai, M. J., Chang, C. J., & Hwang, F. K. (2021). The affordances and limitations of collaborative science simulations: The analysis from multiple evidences. *Computers & Education*, *160*(October 2020), 104029. https://doi.org/10.1016/j.compedu.2020.104029

Liu, Q., Yu, S., Chen, W., Wang, Q., & Xu, S. (2021). The effects of an augmented reality based magnetic experimental tool on students' knowledge improvement and cognitive load. *Journal of Computer Assisted Learning*, *37*(3), 645–656. https://doi.org/10.1111/jcal.12513

Looi, C. K., Zhang, B., Chen, W., Seow, P., Chia, G., Norris, C., & Soloway, E. (2011). 1:1 mobile inquiry learning experience for primary science students: A study of learning effectiveness. *Journal of Computer Assisted Learning*, *27*(3), 269–287. https://doi.org/10.1111/j.1365-2729.2010.00390.x

Lowell, J., & Truscott, W. S. (1986). Triboelectrification of identical insulators. II. Theory and further experiments. *Journal of Physics D: Applied Physics*, *19*(7), 1281–1298. https://doi.org/10.1088/0022-3727/19/7/018

Mutlu-Bayraktar, D., Cosgun, V., & Altan, T. (2019). Cognitive load in multimedia learning environments: A systematic review. *Computers & Education*, *141*, 103618. https://doi.org/10.1016/j.compedu.2019.103618

Olympiou, G., & Zacharia, Z. C. (2012). Blending physical and virtual manipulatives: An effort to improve students' conceptual understanding through science laboratory experimentation. *Science Education*, *96*(1), 21–47. https://doi.org/10.1002/sce.20463

Paas, F., Tuovinen, J. E., van Merriënboer, J. J. G., & Aubteen Darabi, A. (2005). A motivational perspective on the relation between mental effort and performance: Optimizing learner involvement in instruction. *Educational Technology Research and Development*, *53*(3), 25–34. https://doi.org/10.1007/BF02504795

Paas, F. G. W. C., & Van Merriënboer, J. J. G. (1994). Instructional control of cognitive load in the training of complex cognitive tasks. *Educational Psychology Review*, *6*(4), 351–371. https://doi.org/10.1007/BF02213420

Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, *14*, 47–61. https://doi.org/10.1016/j.edurev.2015.02.003

Petersen, G. B., Klingenberg, S., Mayer, R. E., & Makransky, G. (2020). The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education. *British Journal of Educational Technology*, *51*(6), 2099–2114. https://doi.org/10.1111/bjet.12991

Savicki, V., Kelley, M., & Lingenfelter, D. (1996). Gender, group composition, and task type in small task groups using computer-mediated communication. *Computers in Human Behavior*, *12*(4), 549–565. https://doi.org/10.1016/S0747-5632(96)00024-6

Stahl, G. (2005). Group cognition in computer-assisted collaborative learning. *Journal of Computer Assisted Learning*, *21*(2), 79–90. https://doi.org/10.1111/j.1365-2729.2005.00115.x

Theiner, G. (2014). Varieties of group cognition. In *The Routledge handbook of embodied cognition*. New York: Routledge. https://doi.org/10.4324/9781315775845

Tolentino, L., Birchfield, D., Megowan-Romanowicz, C., Johnson-Glenberg, M. C., Kelliher, A., & Martinez, C. (2009). Teaching and learning in the mixed-reality science classroom. *Journal of Science Education and Technology*, *18*(6), 501–517. https://doi.org/10.1007/s10956-009-9166-2

Turan, Z., Meral, E., & Sahin, I. F. (2018). The impact of mobile augmented reality in geography education: achievements, cognitive loads and views of university students. *Journal of Geography in Higher Education*, *42*(3), 427–441. https://doi.org/10.1080/03098265.2018.1455174

van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, *17*(2), 147–177. https://doi.org/10.1007/s10648-005-3951-0

Wang, C., Fang, T., & Gu, Y. (2020a). Learning performance and behavioral patterns of online collaborative learning: Impact of cognitive load and affordances of different multimedia. *Computers & Education*, *143*(5), 103683. https://doi.org/10.1016/j.compedu.2019.103683

Wang, C., Fang, T., & Miao, R. (2018). Learning performance and cognitive load in mobile learning: Impact of interaction complexity. *Journal of Computer Assisted Learning*, *34*(6), 917–927. https://doi.org/10.1111/jcal.12300

Wang, C., Ma, Y., & Wu, F. (2020b). Comparative learning performance and mental involvement in collaborative inquiry learning: Three modalities of using virtual lever manipulative. *Journal of Science Education and Technology*, *29*(5), 587–596. https://doi.org/10.1007/s10956-020-09838-4

Wang, T.-L., & Tseng, Y.-K. (2018). The comparative effectiveness of physical, virtual, and virtual-physical manipulatives on third-grade students' science achievement and conceptual understanding of evaporation and condensation. *International Journal of Science and Mathematics Education*, *16*(2), 203–219. https://doi.org/10.1007/s10763-016-9774-2

Wong, L. H., & Looi, C. K. (2011). What seams do we remove in mobile-assisted seamless learning? A critical review of the literature. *Computers & Education*, *57*(4), 2364–2381. https://doi.org/10.1016/j.compedu.2011.06.007

Wu, P.-H., Hwang, G.-J., Yang, M.-L., & Chen, C.-H. (2018). Impacts of integrating the repertory grid into an augmented reality-based learning design on students' learning achievements, cognitive load and degree of satisfaction. *Interactive Learning Environments*, *26*(2), 221–234. https://doi.org/10.1080/10494820.2017.1294608

Zacharia, Z. C., & Michael, M. (2016). Using physical and virtual manipulatives to improve primary school students' understanding of concepts of electric circuits. In *New developments in science and technology education* (pp. 125–140). Springer. https://doi.org/10.1007/978-3-319-22933-1_12

Zheng, B., Warschauer, M., Lin, C. H., & Chang, C. (2016). Learning in one-to-one laptop environments: A meta-analysis and research synthesis. *Review of Educational Research*, *86*(4), 1052–1084. https://doi.org/10.3102/0034654316628645

Appendix A. Inquiry guidance and group worksheet

Inquiry guidance and group worksheet		
	Task 1 (see Figure 1a)	Task 2 (see Figure 1b)
Operation guidance	Rub the yellow balloon against the sweater and observe the change of the balloon and sweater.	Rub the yellow balloon and the green balloon against the sweater respectively, and observe the changes of the balloon and sweater.
Step-by-step inquiry questions	1. Do positive (10 points) and negative (10 points) charges move? How did they move?	Please mark the initial positions of the yellow balloon and the green balloon in the Figure (10 points).
	2. What happens when the balloon is close to the sweater after friction (5 points)? Why is that (10 points)?	Use one of the balloons to suck away all the negative charges on the sweater. What happens to the position of the balloon by doing this (10 points)? Why (10 points)?
	3. What happens when the balloon is close to the charging wall after friction (10 points)? Why is that (5 points)?	Can the yellow balloon and the green balloon maintain the initial position when they each absorb a part of the negative charges of the sweater (10 points)? Why (10 points)?

Appendix B. Questionnaires

Cognitive load

Mental load

1. The degree of difficulty of this learning activity for me.
2. The degree of difficulty of this learning content for me.
3. The degree of difficulty of this related knowledge for me.
4. The degree of difficulty of this learning process for me.

Mental effort

1. The degree of mental effort I invested into the learning activity.
2. The degree of energy I devoted to the learning activity.
3. The degree of time tension during the learning activity.
4. The degree of nervousness during the learning activity.

Group-process Satisfaction

1. I felt that I could express my thoughts when I had an idea about the problem.
2. I felt that people listened to my thoughts when I expressed them.
3. I felt that people understood my thoughts and feelings after I expressed them while solving this problem.
4. I felt good that I could participate with my group in coming to a conclusion about the problem.

Open questions

1. How did your group members collaborate through tablet(s)?
2. What difficulties did your group encounter during the collaboration?