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How Tablet-Student Ratio and External Scripts Affect Knowledge Acquisition and Cognitive Load in Scientific Collaborative Inquiry Learning? A Three-Round Quasi-Experiment

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Abstract
With the advancement of informational and portable technologies, virtual manipulatives based on tablets are applied to support students' learning in science education. However, research on the impact of tablet-student ratios on individual knowledge acquisition and cognitive load in collaborative inquiry learning has not been addressed in detail yet. The purpose of this study is to examine the influence of tablet-student ratios (1:1 or 1:m) and external script availability (with or without) on students' knowledge acquisition and cognitive load in collaborative inquiry learning when using virtual manipulatives. A three-round quasi-experiment was conducted across 3 months with 130 fifth graders from four classes learning three scientific inquiry themes. The four classes, class A (1:1 group with external script condition) with 31 students, class B (1:m group with external script condition) with 34 students, class C (1:1 group without external script condition) with 33 students, and class D (1:m group without external script condition) with 32 students, constitute four technology affordance conditions. The research conducted a pretest, posttest, and repeated-measures ANOVA to explore the effects of technology affordances on students' knowledge acquisition and cognitive load of collaborative learning. Results show that technology affordances have impacts on students' knowledge acquisition and cognitive load during collaborative inquiry activities. Moreover, the impacts changed over time. This study has practical implications for the instructional design of mobile device-supported collaborative inquiry activities.

Keywords Tablet-student ratio · External script · Virtual manipulative · Collaborative learning · Knowledge acquisition · Cognitive load

Introduction

Scientific inquiry learning encourages students to conduct experimental activities and acquire knowledge by themselves (Pedaste et al., 2015), wherein the affordance of instructional technology is a topic worthy of attention. Commonly, there are usually two types of instructional technologies for collaborative inquiry activities. One is the digital learning tools for science inquiry. For digital learning tools, one prime example is virtual manipulatives (VM), which are simulations modeled after physical manipulatives (PM) (Moyer et al., 2002). For instance, virtual labs run on mobile devices can afford students to conduct scientific experiments (Zacharia & Olympiou, 2011). Another aspect of instructional technologies in collaborative inquiry learning is the collaboration script, a traditional instructional technology rather than a digital technology (Vogel et al., 2017). As a typical kind of collaboration script, external scripts (ES) designed and distributed to groups by teachers could afford groups with structured group processes and collaboration skills during collaborative inquiry learning (King, 2007). On the whole, the above instructional technologies could provide certain technology affordances for mobile devices-supported collaborative inquiry, such as information collection, resource sharing, and strategic coordination

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between group members (Jeong & Hmelo-Silver, 2016; Wang et al., 2020a).

For the adaptation of mobile devices in science education, the device-student ratio becomes a topic worthy of discussion. Former research has found that the 1:1 ratio had benefits on students' learning gains they could experience seamless resource acquisition anytime and anywhere (e.g., Wong & Looi, 2011; Zheng et al., 2016). Meanwhile, researchers in the mobile learning field call for a new understanding of device-student ratios (Wang et al., 2020b), such as the comparison of 1:1 and 1:m ratios in concept mapping teamwork (Lin et al., 2012) and scientific inquiry learning (Wang et al., 2020b). Concretely, the 1:1 ratio for a group refers to each student having an operable VM based on the mobile device (e.g., tablets), while there is only one VM in a group in the 1:m condition. Previous studies suggest that VM runs on tablets could provide students with rich interactive experiences (Guzmán & Joseph, 2021), and device-student ratios could affect the ways of peer interaction (Wang et al., 2020b) and corresponding collective learning products (Lin et al., 2012) in face-to-face classrooms. However, the impact of device-student ratios on individual knowledge acquisition remains rare.

To sum up, technology affordances for collaborative inquiry learning in this study embrace the tablet-student ratio (1:1 or 1:m) when using VM based on tablets and the availability of ES (with or without) as well. On the one side, when adopting VM based on tablets, students have to interact with both the VM and group members; this may increase students' cognitive load and impact corresponding academic gains (Chu, 2014; Van Merrienboer & Sweller, 2005). On the other side, ES could benefit the cognitive resources allocation among group members by reducing the cognitive load (Dillenbourg & Betrancourt, 2006; Wang et al., 2020a). However, when interacting with group members and different technology affordances in face-to-face collaboration, the changes in the cognitive load of students have been ignored. In the current study, a three-round quasi-experiment was conducted to explore how the two technology affordances for tablet-supported collaborative inquiry influence knowledge acquisition and cognitive load.

Literature Review

Inquiry-Based Collaborative Learning

Inquiry-based collaborative learning proves essential for students in the twenty-first century (Chan & Pow, 2020). As a student-centered approach, inquiry-based collaborative learning emphasizes interaction among learners and aims to help students attain a deeper understanding of learning concepts through inquiry activities (Bell et al., 2010; Ellis & Bliuc, 2015). Studies have found that inquiry-based collaborative learning appears effective in promoting students' learning motivation, engagement, problem-solving skills, and critical thinking (Liu et al., 2021; Lu et al., 2021). In science education, instructors adopt inquiry-based collaborative learning activities to improve students' knowledge acquisition by scientific inference and problem-solving (García-Carmona, 2020). As for the design model of scientific collaborative inquiry learning, Pedaste et al. (2015) proposed an inquiry cycle with five learning stages: orientation, conceptualization, research, conclusion, and discussion, which is widely used in conducting inquiry-based collaborative learning. Inquiry learning models have also been affected by technological development. On the one hand, the processing of information technology led to a revolution in software, such as low-cost, easily accessible, virtual versions of inquiry tools (Liu et al., 2021). On the other hand, hardware, such as portable mobile phones, expands the inquiry-based collaborative learning interactive experience and makes the inquiry-based collaborative learning processes ubiquitous and flexible (Crompton et al., 2017). A meta-analysis of mobile learning by Sung et al. (2016) has found that the inquiry learning method plays the strongest positive role in students' learning performance among many teaching approaches. In general, it is worth paying more attention to mobile technology-based collaborative inquiry learning and finding best practices of the approach.

VM and Mobile Device-Student Ratio

Manipulatives are widely adopted in science education for hands-on activities (Koning & Tabbers, 2011). The virtual version of a manipulative (VM) is often designed by simulating the corresponding physical one, and it can be easily accessed on digital devices (Moyer et al., 2002). As a digital learning tool, VM has the following affordances for learning science knowledge by manipulations (Olympiou & Zacharia, 2012): observing unobservable phenomena in real life, repeating measurements, evading dangerous operations, etc. Meanwhile, with the increasing usage of mobile devices in science classrooms, VM adaptation becomes more convenient for inquiry learning activities (Min et al., 2016). VM based on a tablet PC is a popular inquiry tool in science inquiry activities (e.g., Fokides & Mastrokoukou, 2018). For instance, Reychav and Wu (2015) developed a geographical collaborative system running on tablets. It was found that collaborative learning activities based on mobile devices could afford abundant communication as it contains face-to-face interactions (Reychav & Wu, 2015).

Concerning the mobile device-student ratio, a 1:1 ratio can optimize students' learning experiences because of the affordances of mobile technologies in supporting information integration and social knowledge construction (Harper & Milman, 2016; Wong & Looi, 2011). For instance, in the experimental study of Reychav and Wu (2016), students in groups all have access to operate their own mobile devices during collaborative inquiry work. Besides, in some situations, students are allocated only one VM in a group (e.g., Ha & Fang, 2018). This is similar to the PM usage during the collaborative inquiry. For example, Fokides and Mastrokoukou (2018) adopted VM based on tablet PCs for primary students to conduct group inquiry tasks. Students were asked to operate on one VM in pairs, and it was found that students using tablet PCs performed better than traditional instructor-led inquiry learning. Another example is the comparison of 1:1 and 1:m ratios in collaborative concept mapping activities by Lin et al. (2012). Their study found that students in the 1:m ratio performed better than those in the 1:1 ratio; however, the study did not further explain the reason for this result. Therefore, when adopting VM in collaborative inquiry learning, there is a need to find more details of how knowledge acquisition varies under different mobile device-student ratios. Furthermore, in the study of Wang et al. (2020b), students in the 1:m ratio condition had higher task involvement and group worksheet scores than students in the 1:1 ratio condition in collaborative scientific inquiry learning. However, previous studies rarely involved whether students could gradually adapt to the given conditions over time. In other words, is it true that as time goes by, students become more familiar with the given conditions, and their learning performance will be better?

External Scripts for Collaboration

Collaboration scripts are scaffolds that facilitate collaboration by structuring the interactive processes of groups (Fischer et al., 2007). Scripts involved in the collaboration are designed to prompt specific cognitive, socio-cognitive, and metacognitive processes, so that the intended learning actions could happen, such as the roles of participants and the sequence of events (King, 2007). Internal script and external script (ES) are two common types of collaboration scripts. An internal script is developed from the long-term cooperation within the group, including roles, distribution of labor, and interaction mode, which is related to the skills and cooperation experience of the group members (Vogel et al., 2017). By contrast, ES are designed externally in classroom settings by a teacher or a facilitator and explicitly imposed on learners (King, 2007). Generally, there are five types of external scripts: induced scripts, instructed scripts, trained scripts, prompted scripts, and follow-me scripts (Dillenbourg, 2002). Instructed scripts and prompted scripts are frequently used for group inquiry tasks (Dillenbourg & Jermann, 2007). Specifically, instructed scripts convey conveys instructors' expectations for the manners of interaction within groups when solving problems (Dillenbourg, 2002); prompted scripts give suggestions on the role-taking of group members, such as "analyzer" or "critic" (Dillenbourg & Jermann, 2007). ES play an important role on coordinate and promotes effective cooperation and interaction. Group members could develop a cognitive independent scheme on how to effectively coordinate interactive actions, share collective knowledge, and appropriately allocate available information for task execution (Kirschner et al., 2018). In addition, the impact of ES on collaborative discussion is related to the groups' prior experience and familiarity with the script (Mende et al, 2017). ES may gradually be integrated into the internal coordination of groups over time, as familiarity could grow over time (Fischer et al., 2007; Wang & Le, 2022).

Cognitive Load Theory and Related Studies

Cognitive load relates to the total amount of information that working memory in one's brain can manage at one time (Sweller et al., 1998; Van Merrienboer & Sweller, 2005). Regarding the cognitive load framework by Paas and Van Merrienboer (1994), there are two indicators of cognitive load: mental load and mental effort (Paas & Van Merrienboer, 1994). Specifically, the mental load is associated with the formats of information presented in learning materials and tasks, which is considered to be independent of subject characteristics and constant for a given task; mental effort is related to the amount of capacity or resources that are actually allocated to accommodate the task demands, and it reflects the amount of controlled processing in which the individual is engaged (Paas & Van Merrienboer, 1994). Moreover, a high mental load typically comes with a high mental effort (Van Merrienboer & Sweller, 2005). The composition of cognitive load is complex, and researchers have not yet reached a unified understanding of the concept and dimension division. Another well-known classification of cognitive load types was proposed by Sweller et al. (1998). According to the cognitive load theory of Sweller et al. (1998), there are three types of cognitive load: extraneous cognitive load, intrinsic cognitive load, and germane cognitive load. Extraneous load is imposed by information elements unrelated to the learning task such as the way the information or the task is presented; the intrinsic load is associated with the inherent complexity of the information that needs to be processed (Kirschner et al., 2018). Germane load is associated with the efforts of learners which are used to process and comprehend the learning task (Sweller et al., 1998). However, some researchers noted that germane load may be redundant in the framework, as it is essentially indistinguishable from the intrinsic load (Kalyuga, 2011; Kirschner et al., 2018). Therefore, we decided to use the classification of mental load (extraneous) and mental effort (intrinsic) (Paas & Van Merrienboer, 1994) and adopt relevant measure scales (Paas, 1992).

In the mobile learning field, researchers often introduce the measurement of cognitive load (e.g., Lin & Lin, 2016; Wang et al., 2018). However, the influence of cognitive load on learning performance when adopting mobile devices has not been consistently reached. Some studies find that a high cognitive load leads to low learning performance (Chu, 2014; Lin & Lin, 2016); some indicate that high learning performance needs a highly engaged cognitive load (Wang et al., 2018). In the science education field, former studies related to VM paid more attention to students' knowledge acquisition (e.g., Ha & Fang, 2018), yet few relevant studies involved the measurement of cognitive load. Some studies, from the perspective of multimedia design, hold that the high degree of simulation of VM may cause a high irrelevant cognitive load (Olympiou & Zacharia, 2012). As for the relationships between technology affordances in collaborative learning and cognitive load, studies have found that appropriate technological design, especially the ones that facilitated convenient information exchange, could reduce students' cognitive load and lead to high performance in knowledge retention (Wang et al., 2020a).

For the relationship between ES and learners' cognitive load, it was found that, in some situations, ES help reduce the external cognitive load generated by interactive activities and has a positive influence on group work (Kirschner et al., 2018). For instance, with proper suggestions on labor distributions and procedure sequence, students could offload interaction management on ES, and then they will have more time to focus on the content itself and the collaborative learning tasks (Dillenbourg & Betrancourt, 2006; King, 2007). On the contrary, over-scripting may cause extraneous load as students have to pay more attention to the understanding of a complex script (Dillenbourg & Jermann, 2007). Moreover, over-scripting gives little freedom for group members to have a productive group process (Dillenbourg, 2002). Besides, it has already been found that unreasonable cognitive resource allocation is harmful to students learning performance (Sweller et al., 1998). Furthermore, students' familiarity with instructional technologies could also affect their cognitive load during the learning process (Zhang et al., 2016; Wang et al., 2020a). However, few empirical studies examined the changes in the cognitive load of students when providing ES for group work for a long time.

Purposes of This Study

Inspired by the above theoretical and empirical studies, we assume that tablet-student ratios (TSR) and ES availability (ESA) could influence students' cognitive load during collaborative inquiry learning and corresponding knowledge acquisition. To be specific, the TSR variable has two conditions: 1:1 and 1:m mobile device-student ratios, respectively. Meanwhile, the ESA (with or without) refers to whether to provide external support structuring the interactive processes, such as suggestions on role appointments. This study aims to compare the knowledge acquisition and cognitive load of groups under different TSR and ESA conditions. In addition, we also tend to explore the effects of the above conditions on knowledge acquisition and cognitive load over time, as the adaptation of instructional technologies may also matter for group coordination. To explore these issues, we conducted a series of collaborative inquiry learning activities in four classes in a primary school to depict the impact of instructional technologies on collaboration. Accordingly, two research questions are presented as follows:

1. How did TSR and ESA affect students' knowledge acquisition? How did the effects change over time?
2. How did TSR and ESA affect students' cognitive load? How did the effects change over time?

Methods

Participants

In total, 130 fifth-grade elementary school students volunteered to participate in this study. They came from four science classes in the chosen public elementary school located in Beijing, China. All participants were at the age of 10–12. Also, they were taught by the same science teacher. As shown in Fig. 1, the four classes in this study were randomly coded as A, B, C, and D and were separated into the four conditions, namely, TSR (1:1 vs 1:m) and ESA (with vs without). Concretely, 31 students (15 boys, 16 girls) in class A were asked to have a 1:1 group with an external script condition; 34 students (16 boys, 18 girls) in CLASS B were assigned to a 1:m group with an external script condition; 33 students (16 boys, 17 girls) in class C were in 1:1 group without external script; 32 students (13 boys, 19 girls) in class D were offered in 1:m group without external script condition. The students involved in this study had not learned about the inquiry themes before the experiment. Besides, one-way ANOVA shows no significant difference on the final grades of the last academic year among these four classes (F [3, 125] = 1.716, p = .167 > .05), which showed each class had

Fig. 1 Collaborative inquiry learning situations

a similar academic level in a science discipline. Moreover, a pretest including three pieces of test items was conducted to measure students' prior knowledge per theme. One-way ANOVA of grades of the pretest shows no significant difference on the level of previous knowledge among the four classes (F [3, 126] = .204, p = .894 > .05).

Each class contains 6 groups with 5–6 students in a group. In classroom settings, there were some students not fully involved in the whole process of the experiment because of sick leave or extra-curricular activities. That is, not all students attended the entire experiment in this study which could be viewed as a limitation. Specially, 115 of the 130 (88.46%) students completed the 3-round post-test, and 119 (91.54% of 130) students completed the 3-round questionnaire session. Accordingly, the data of the students who fully participated in the post-tests or questionnaire sessions will be analyzed.

Inquiry Tools

Virtual Manipulatives

We selected three inquiry themes according to the science curriculum of the selected school: refraction of light (RL) in the unit of light, electrical circuits (EC) in the unit of electricity, and electromagnetic induction (EI) in the unit of magnetic. Corresponding VMs adopted in this study are interactive simulation tools from the PhET learning platform (phet.colorado.edu), which is a free online simulation program for physics, chemistry, mathematics, earth science, and biology. The screenshots of the three VMs from PhET were shown in Fig. 2. The simulations are animated and interactive environments where students learn through exploration. Moreover, PhET simulations are in the form of HTML 5, which can be accessed easily via browsers on tablets.

The selected elementary school had a specialized science classroom for science courses, in which adequate tablets are available for the adoption of VMs. All participating pupils had more than 4 years of experience in using tablets for learning before they conducted science inquiry experiments in groups.

External Scripts

The function of ES in our study is to give suggestions on group processes and intra-group interaction. The designed ES contained two contents: an instructed script and a prompted script. The ES were imposed on groups before (instructed script) and during (prompted script) each collaborative inquiry activity. Before each collaborative inquiry activity, the science teacher gave guidance and advice on collaborative actions through a slide in front of the class with ES, including clarifying inquiry goals, practice and thought, thinking aloud, integrating and perfecting, and drawing a conclusion (see Appendix 1 ES before inquiry). In addition, the slide shown in front of the class also contains the introduction of the two inquiry tasks of each learning theme, while the content and procedure of inquiry tasks were not regarded as scripts. For those groups without ES, the slide shown before collaborative activities only contains the introduction of inquiry tasks. During the inquiry activities, the content of ES was distributed to scripted groups in the form of a paper card (see Appendix 2 ES during inquiry). The ES asked groups to select a member to serve as the role of "inspector." The designed function of the inspector aimed to regulate the inquiry process and keep group members engaged in the discussion.

Experimental Procedure

In this study, each learning theme had the same experimental procedure. Based on a comprehensive literature review of inquiry by Pedaste et al. (2015), it forms an inquiry cycle including five stages: (1) orientation, (2) conceptualization, (3) investigation, (4) conclusion, and (5) discussion. Some of these stages can be divided into sub-phases. These inquiry phases can help teachers guide their students by highlighting key steps. Thus, the scientific inquiry activities in this study were designed following Pedaste et al.'s (2015) inquiry phases. Each round of inquiry experiment (RL, EC, and EI) followed the same experimental procedure. The detailed experimental procedure (see Fig. 3), and their corresponding inquiry phases are described as follows.

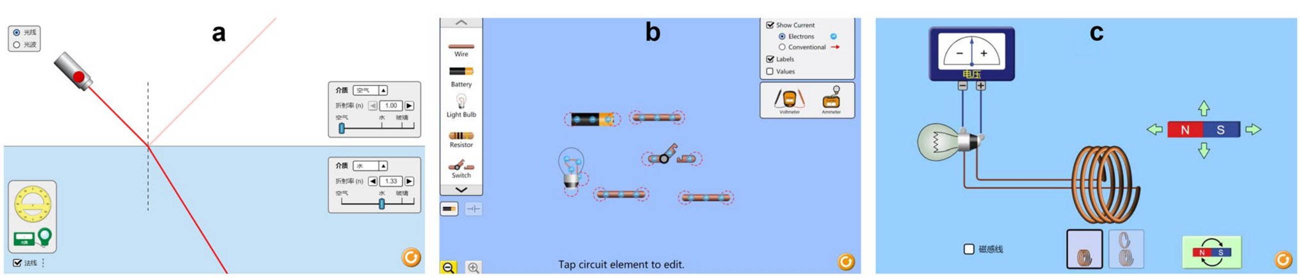

Fig. 2 Three themes of virtual manipulatives: **a** RL, **b** EC, and **c** EI

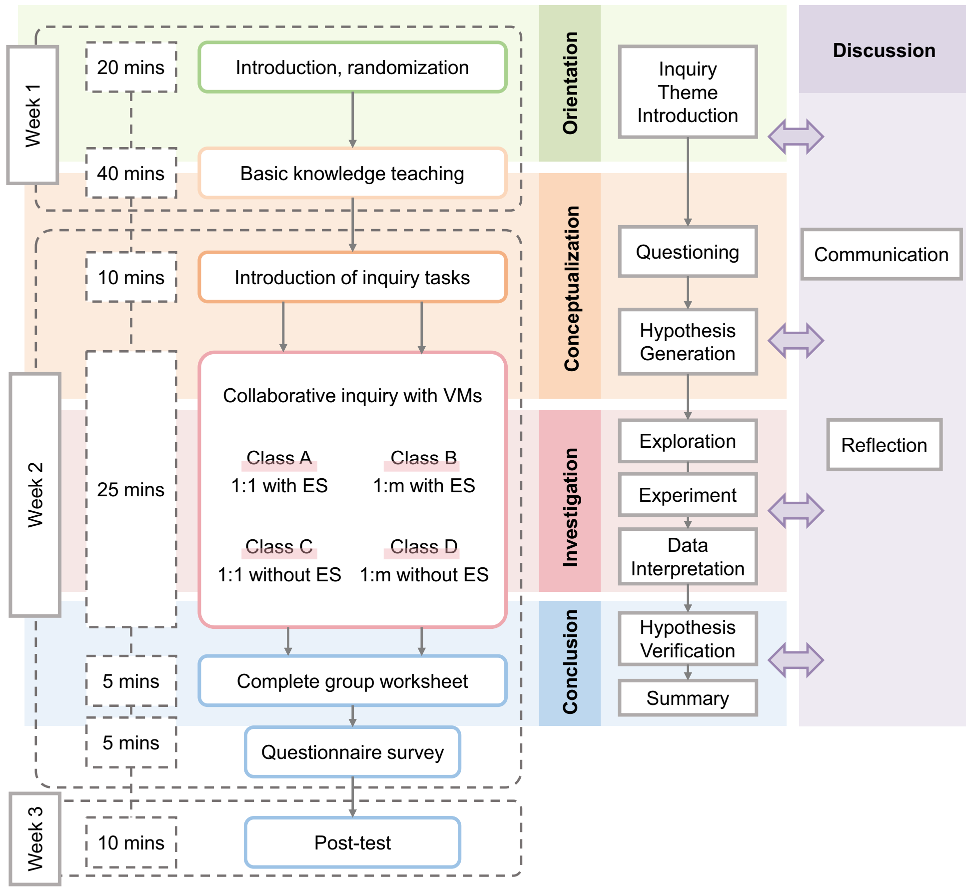

Fig. 3 Diagram of experiment design

In the first week, two parts were conducted in the experiment: introduction and randomization (20 min), and basic knowledge teaching (40 min). In the first part, the teacher gave a brief introduction to inquiry activities. Then, students were randomly assigned to four technology affordance conditions. In the second part, the science teacher then taught the basic knowledge of the learning theme (RL/EC/EI). An overview of the inquiry theme was given in this week, which corresponded to the orientation phase.

In the second week, the conceptualization phase includes four parts: introduction of inquiry tasks (5 min), collaborative inquiry with VMs (25 min), complete group worksheet (5 min), and questionnaire survey (5 min). In the first part, inquiry tasks were introduced by the science teacher. After that, each group was provided with a paper-based group worksheet, which prompted the collaborative inquiry learning procedure under four different learning conditions. In the second part, collaborative inquiry with VMs, group members work together to conduct inquiry tasks under given technology affordance conditions. In the third part, groups check and finally completed the group worksheet. The last part involved participants completing a questionnaire. As shown in Fig. 3, the second week contains three inquiry phases: conceptualization, investigation, and conclusion. The conceptualization phase includes two sub-phases: questioning in the introduction of inquiry tasks and hypothesis generation when the group worksheet was given to groups. The investigation phase includes three sub-phases: exploration, experimentation, and data interpretation, and all these sub-phases were supported by VMs. The conclusion phase includes two sub-phases: hypothesis verification and summary of findings for the completion group worksheet.

In the last week, a post-test (10 min) related to the corresponding inquiry theme was conducted. The post-tests were adopted to evaluate students' knowledge acquisition of the learning themes.

To ensure that all rounds of inquiry were conducted under the same intervention procedure, students' inquiry process was mainly organized by the science teacher, and the first author served as an assistant to maintain the experimental procedure and control irrelevant variables. Data were collected from the three-round experiment in four classes according to three different themes. To be specific, learning RL for a month in April, EC for a month in May, and EI for a month in June.

Group worksheets of the three selected inquiry themes were jointly developed by the science teacher and researchers about the science curriculum standards. Students conduct inquiry tasks following the task requirements on group worksheets. Each group worksheet includes two inquiry tasks (see Appendix 3 inquiry tasks in group worksheets). The first task was to help students interpret experiment phenomena, which facilitated students' concept interpretation. The second task assisted students in understanding the fundamental principles of the inquired theme, which aimed to enhance students' capability in problem-solving. In our study, group worksheets and ES have different functions. ES provide collaboration skills and structured processes, while group worksheets created problem-solving context situations and listed reasonable inquiry tasks for groups.

Instruments

The instruments used in the experiments contain three versions of post-tests and a questionnaire to collect students' knowledge acquisition and cognitive load during collaborative inquiry activities.

Test Tools

The post-tests were intended to evaluate students' knowledge acquisition of the three learning themes (e.g., RL, EC, and EI). Each round of post-test has a total score of 60 points and includes a completion, a true or false question, and four multiple-choice questions. Sample items for post-tests are shown in Appendix 4. Each post-test was conducted 1 week later after the corresponding inquiry activity. The Guttman Split-half coefficient of the three post-tests were 0.501, 0.636, and 0.616, respectively, indicating acceptable reliabilities.

All items in the above tests were designed by the science teacher and researchers referring to Beijing elementary science question bank. Learning objectives and functions of the VMs adopted were also taken into consideration when developing group worksheets and corresponding tests. Another science teacher who owned over 10 years of science teaching experience was asked to check these tests.

Questionnaire

The questionnaire used after each round of the scientific inquiry experiment contains a cognitive load scale. The cognitive load scale was adapted from the versions developed by Paas (1992) and Wang et al. (2018). The scale consists of mental load and mental effort dimensions with four seven-point Likert rating items in each (see Appendix 5 cognitive load scale). One sample item for mental load is "The difficulty of this learning content for me"; one sample item for mental effort is "The degree of energy I devoted to the learning activity." The Cronbach's alpha values were 0.955 and 0.711 for ML and ME in the first round of the experiment (RL), 0.946 and 0.718 for ML and ME in the second round of experiment (EC), and 0.952 and 0.733 for ML and ME in the third round of experiment (EI), respectively. These values show that the scale adopted in the study had acceptable reliability.

Statistical Analysis

A mixed experimental design was adopted in this study, as there were three rounds of quasi-experiments (i.e., RL, EC, and EI). The mixed experimental design refers to research including both the between-subject factors and the within-subject factors (Leon & Heo, 2009). The within-subject factor usually refers to time, that is, repeated experiments are carried out at different time periods under the same experimental conditions. In this study, TSR (1:1 vs 1:m) and ESA (with vs without) are the two between-subject factors, which constitute the same experimental conditions for each round of quasi-experiments. Moreover, the times of different learning themes, RL, EC, and EI, could be viewed as the early, middle, and late periods of the entire quasi-experimental study (see Fig. 4). Thus, the within-subject factor of time could reveal the change of the temporal effect of technology affordances to some extent. It is worth mentioning that the learning contents and VMs in the three learning themes are different, although we have tried to control the flow and time of each round of the experiment. In order to reduce this limitation, we standardize the dependent variables, so as to minimize the impact of learning contents.

Knowledge acquisition and cognitive load are the two dependent variables. To explore the effects of technology affordances (TSR and ESA) on students' knowledge acquisition and cognitive load over time, we standardized the post-test scores of students by using T scores ($T = 50 + 10Z$, Z = z-score). Meanwhile, the data collected by the cognitive load scale is already hierarchical and standardized, as it adopted a Likert rating. Then, a repeated measurement ANOVA was applied to analyze the post-test scores and cognitive load scores. Specifically, we analyzed the between-effect and within-effect after Mauchly's test of sphericity and reported the corresponding effect size, partial η^2 (Cohen, 1988).

Results

Knowledge Acquisition

A total of 115 of the 130 (88.46%) students completed the 3-round post-test. Table 1 presents the means and standard deviations of scores acquired by students in the four groups in the first (RL), second (EC), and third (EI) post-tests. The between-effect and within-effect variables on students' knowledge acquisition are depicted in Table 2. These effects are introduced in the following sub-sections.

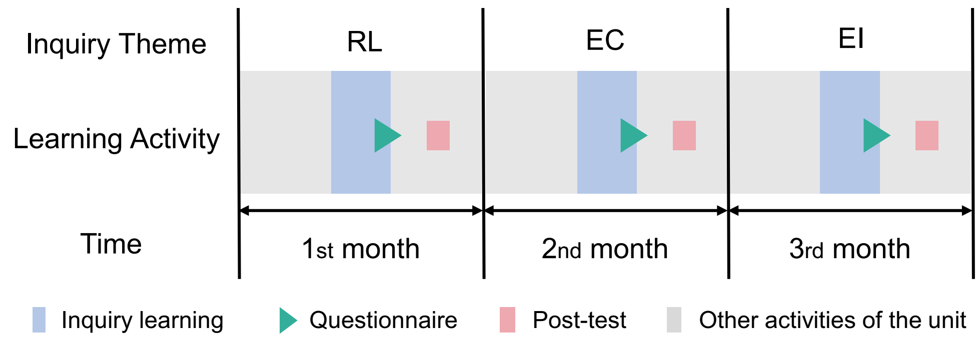

Fig. 4 Time axis of the experiment

Between-Effect

The test of between-subject effects showed that TSR (F [1, 111] = 1.200, p = .276 > .05, partial η^2 = .011 < .05), ESA (F [1, 111] = 0.468, p = .495, partial η^2 = .004 < .01), and the interaction between TSR and ESA (F [1, 111] = .892, p = .347, partial η^2 = .008 < .01) had no significant effect on knowledge acquisition (see Table 2).

Within-Effect

The test of within-subject effects showed that the time × ESA interaction on knowledge acquisition was statistically significant (F [2, 222] = 10.808, p < .001, partial η^2 = .089) (see Table 2). We provided the means and standard deviations of scores in Table 3.

The knowledge acquisition of students with ES was significantly higher than that of students without ES (mean difference (MD) = 4.977, p = .007 < .01, partial η^2 = .064) in the first time round (RL). The ES group has significantly lower post-test scores than those without ES (MD = −5.032, p = .009 < .01, partial η^2 = .060) in the second time round (EC). The results showed that the influence of ES on the knowledge acquisition of students was influenced by experimental time. However, the ESA had no significant influence on students' knowledge acquisition in the last round experiment (MD = −2.617, p = .152 < .01, partial η^2 = .018).

Furthermore, in the case of students with ES, the students' post-test scores in the first time round (RL) were higher than that in the middle time round (EC) (MD = 5.359, p = .001 < .01), while no obvious differences were found between the time of RL and EI (MD = 3.336, p = .134 > .05). In the condition of students without ES, the post-test scores of students in the first time round (RL) were lower than (EC) (MD = −4.591, p = .008 < .01) and EI (MD = −4.076, p = .049 < .05). This indicates that ES might have negative effects on students' knowledge acquisition. By contrast, students performed better in the middle and late periods on knowledge acquisition when ES was not provided.

The interactive effect among time, TSR, and ESA was significant (F [2, 222] = 3.223, p = .042 < .05, partial η^2 = .028) (related descriptive results were shown in Table 1). The students' post-test scores in the ES group were significantly higher than those without ES under the 1:m condition in the first time round (RL) (MD = 8.403, p = .001 < .01, partial η^2 = .088). However, the post-test scores of students with ES were significantly lower than those without ES under the condition of 1:1 in the last time round (EC) (MD = −7.288, p = .007 < .01, partial η^2 = .064). Overall, for students' knowledge acquisition, ES had a positive effect in the early

Table 1 Descriptive analysis of knowledge acquisition

Condition		RL		EC		EI		N
TSR	ESA	Mean	SD	Mean	SD	Mean	SD	
1:m	With	55.31	11.60	48.10	13.60	49.58	9.22	27
	Without	46.90	10.19	50.87	7.71	54.19	12.60	30
	Total	50.88	11.58	49.56	10.89	52.01	11.27	57
1:1	With	49.99	7.92	46.36	9.85	48.67	7.57	31
	Without	48.43	8.86	53.65	8.44	49.30	8.67	27
	Total	49.26	8.33	49.75	9.85	48.96	8.03	58
Total	With	52.46	10.08	47.17	11.67	49.10	8.31	58
	Without	47.63	9.53	52.19	8.11	51.87	11.10	57
	Total	50.07	10.06	49.65	10.33	50.47	9.85	115

Table 2 Between-effect and within-effect of knowledge acquisition

Effect		F (1, 111)	p	partial η^2
Between-effect	TSR	1.200	.276	.011
	ESA	0.468	.495	.004
	TSR * ESA	0.892	.347	.008
		F (2, 222)	p	partial η^2
Within-effect	Time * TSR	1.226	.295	.011
	Time * ESA	10.808***	.000	.089
	Time * TSR * ESA	3.223*	.042	.028

The following p-value reported is tagged in the same approach

* $p<.05$; ** $p<.01$; *** $p<.001$

stage under the condition of 1:m and a negative effect in the middle stage under the condition of 1:1.

It showed that students were provided ES, and the knowledge acquisition of students in the 1:m condition was higher than those in the 1:1 condition in the first time round (RL) ($MD=5.319$, $p=.039<.05$, partial $\eta^2=.038$). In addition, when students were in the 1:m condition and ES were available, students' knowledge acquisition in the first time round (RL) was higher than those in the middle time round (EI) ($MD=7.292$, $p=.006<.01$). When students were in the condition of 1:m and without ES, the knowledge acquisition of students in the first time round (RL) was lower than that of in the last time round (EI) ($MD=-7.292$, $p=.006<.01$).

As shown in Fig. 5, the effect of ES on knowledge acquisition acquired by students between conditions (1:m vs 1:1) was related to the experimental stage. Under the 1:m condition, students' knowledge acquisition was more susceptible to the influence of ES, and there was a significantly positive effect of ES on knowledge acquisition in the early stage, while it was no longer significant in the middle and late stages. Under the 1:1 condition, there was a negative effect of ES on students' knowledge acquisition in the middle stage.

Cognitive Load

In total, 119 (91.54% of 130) students participated in the questionnaire session in each round of the experiment. Table 4 presents the means and standard deviations of cognitive load, which includes two dimensions: mental load and mental effort. The between-effect and within-effect of different variables on students' cognitive load are depicted in Table 5. These effects are introduced in the following sub-sections.

Between-Effect

Test of between-subject effects showed that TSR (F [1, 115]$=6.500$, $p=.012<.05$, partial $\eta^2=.053$) was significantly correlated with the mental load of students (see Table 5). Post hoc Bonferroni correction was performed to adjust for multiple testing. For between-subject effects, we only found a significant effect on mental load, that is, the mental load of students in 1:m group was significantly higher than those in 1:1 group ($MD=-0.557$, $p=.012<.05$, partial $\eta^2=.053$).

Table 3 Descriptive analysis of knowledge acquisition e in ESA groups

ESA	RL		EC		EI		N
	Mean	SD	Mean	SD	Mean	SD	
With	52.65	10.08	47.23	11.67	49.13	8.31	58
Without	47.67	9.53	52.26	8.11	51.74	11.10	57

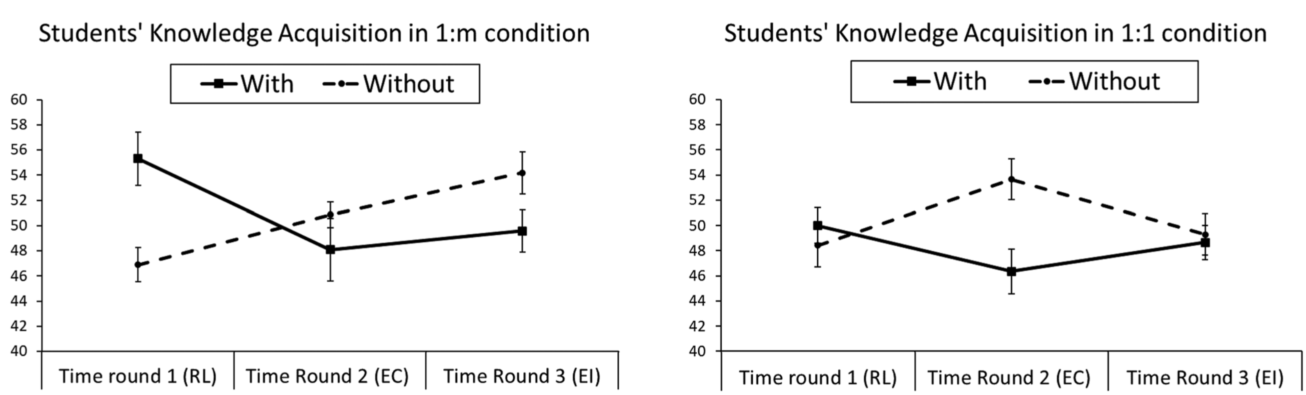

Fig. 5 Mean scores of students' knowledge acquisition over time. Error bars represent standard error

Table 4 Descriptive analysis of cognitive load

Cognitive load	Condition		RL		EC		EI		*N*
	TSR	ESA	Mean	SD	Mean	SD	Mean	SD	
Mental load	1:m	With	3.54	1.85	3.59	1.82	3.82	1.74	29
		Without	3.61	1.48	3.36	1.57	3.07	1.78	31
		Total	3.57	1.65	3.47	1.68	3.42	1.79	60
	1:1	With	2.92	1.81	2.67	1.50	3.15	1.77	30
		Without	2.85	1.21	2.58	1.25	3.47	1.40	29
		Total	2.88	1.54	2.63	1.38	3.31	1.60	59
	Total	With	3.21	1.84	3.11	1.71	3.47	1.77	59
		Without	3.24	1.40	2.98	1.47	3.26	1.61	60
		Total	3.22	1.62	3.04	1.59	3.37	1.69	119
Mental effort	1:m	With	4.31	1.38	4.41	1.74	3.70	1.46	29
		Without	4.14	1.18	4.12	1.33	4.02	1.51	31
		Total	4.22	1.27	4.26	1.53	3.87	1.48	60
	1:1	With	4.23	1.69	4.08	1.65	4.72	1.64	30
		Without	4.11	1.41	3.79	1.26	3.58	1.37	29
		Total	4.17	1.54	3.94	1.47	4.17	1.61	59
	Total	With	4.27	1.54	4.24	1.69	4.23	1.62	59
		Without	4.13	1.28	3.96	1.30	3.81	1.45	60
		Total	4.20	1.41	4.10	1.50	4.02	1.55	119

Within-Effect

As shown in Fig. 6, the test of the within-subject effect showed that the time × TSR × ESA interaction for the mental effort of students was statistically significant (F [2, 230] = 4.254, $p = .015 < .05$, partial $\eta^2 = .036$) (Table 4). Post hoc Bonferroni correction was performed to adjust for multiple testing. It showed that when students were provided with ES, the mental effort of students in the 1:m condition was lower than that of students in the 1:1 condition in the last time round (EI) ($MD = -1.024$, $p = .012 < .05$, partial $\eta^2 = .056$). Besides, in the 1:1 condition, the mental effort of students with ES had a higher level than that of students without ES ($MD = 1.140$, $p = .004 < .01$, partial $\eta^2 = .070$) in the third time round (EI). These results indicate that in the last round of inquiry experiments, ES made students invest more mental effort in the condition of 1:1 than that in the condition of 1: m. While under the condition of 1:1, students with ES paid more mental effort than students without ES.

Table 5 Between-effect and within-effect of cognitive load

Effect	Dimension		F (1, 115)	p	partial η^2
Between-effect	Mental load	TSR	6.500*	.012	.053
		ESA	0.336	.563	.003
		TSR * ESA	0.665	.416	.006
	Mental effort	TSR	0.026	.872	.000
		ESA	1.785	.184	.015
		TSR * ESA	1.251	.266	.011
Effect	**Dimension**		**F (2, 230)**	**p**	**partial η^2**
Within-effect	Mental load	Time * TSR	2.396	.093	.020
		Time * ESA	0.206	.814	.002
		Time * TSR * ESA	1.708	.184	.015
	Mental effort	Time * TSR	2.202	.113	.019
		Time * ESA	0.392	.676	.003
		Time * TSR * ESA	4.254*	.015	.036

*p < .05, **p < .01, ***p < .001

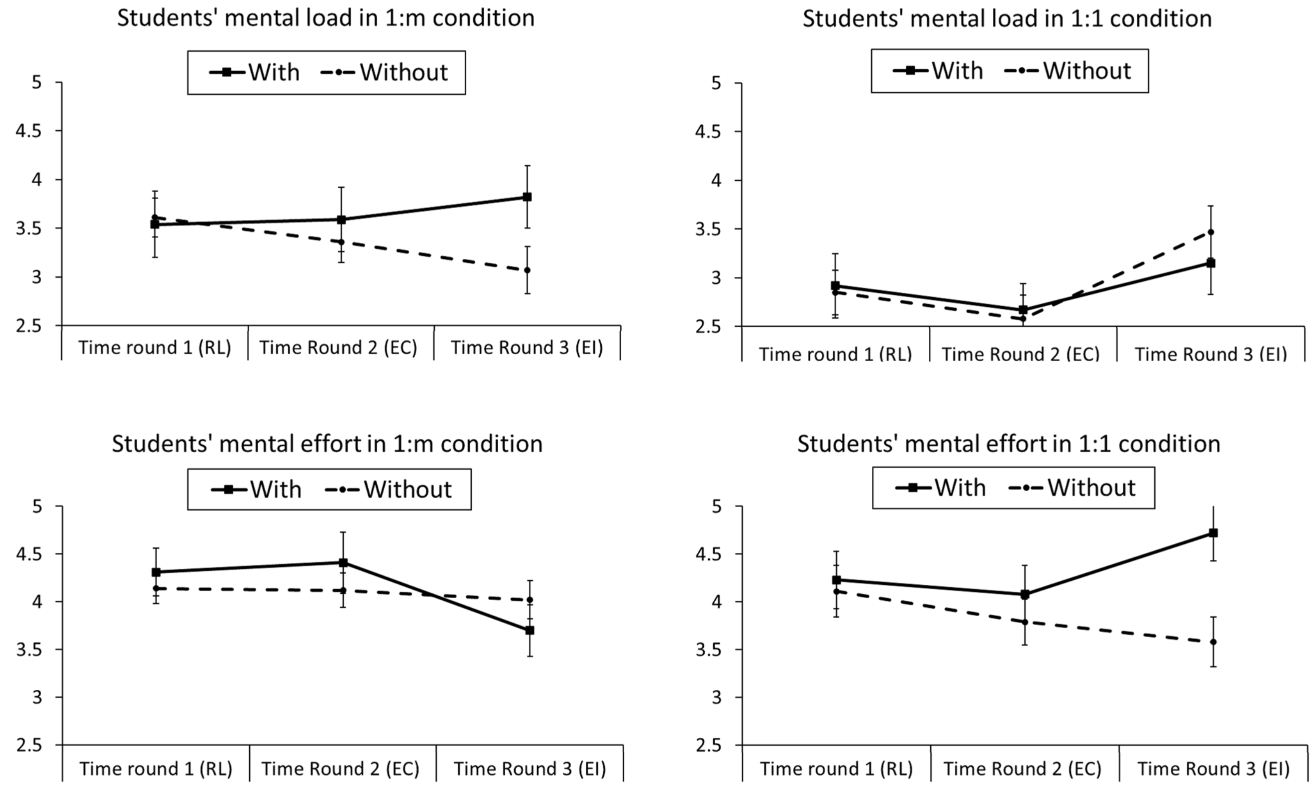

Fig. 6 Mean scores of students' cognitive load over time. Error bars represent standard error

Discussion and Conclusions

In our research, we conducted a three-round quasi-experiment and a repeated-measures ANOVA to explore the effects of technology affordances on students' knowledge acquisition and cognitive load for collaborative learning. Technology affordances in this study contain two aspects, that is, TSR (1:1 vs 1:m) and ESA (with vs without), which showed different effects on knowledge acquisition and cognitive load over time.

How Did TSR and ESA Affect Students' Knowledge Acquisition?

By analyzing collected data, we could draw that TSR and ESA had no significant effect on knowledge acquisition from the overall effect of the experiment. From the perspective of the theme sequence, the time × ESA interaction for knowledge acquisition was statistically significant. Besides, the interactive effect among time, TSR, and ESA was statistically significant. The amount and type of support provided for students will affect their ability to perform operations and, thereby, will influence their experience and performance in the process of cooperative learning.

Under the 1:m condition, the positive effect of ESA on students' knowledge acquisition only showed in the early period. However, under 1:1 condition, it showed a positive effect of ES on students' knowledge acquisition in the middle and late periods. The findings provided additional evidence to the view that environment and task as action constraints will affect the learning process (Abrahamson & Sánchez-García, 2016) and thus cause different knowledge acquisitions. In this study, the mobile device-student ratio (1:1 or 1:m) when using VM was an environmental constraint, and ESA (with or without) was an action constraint. They worked together to affect the learning process. Under the 1:m condition, when only a few students had the chance to operate VM in the early stage, ES could help attract students' attention in groups and create a positive effect. After the ES adapted to the internal script of the team (Fischer et al., 2007), students might unload the ES and pay more attention to TSR. Under 1:1 condition, students had a chance to operate VM individually. ES was an excessive burden to students in the early stage. With a better upstanding of TSR during the learning process, especially in the middle and late periods, ES showed a positive effect on students' knowledge acquisition.

How Did TSR and ESA Affect Students' Cognitive Load?

To answer the second research question, we adopted the cognitive load classification of mental load (extraneous) and mental effort (intrinsic) (Kalyuga, 2011; Paas & Van Merrienboer, 1994) and used questionnaires after each round of the experiment to investigate students' cognitive load. In terms of mental load, it is shown that ESA had no significant effect on the mental load of students, while TSR was significantly correlated with students' mental load. The findings echo the viewpoint of Chu's study (2014): the mental load is associated with the quantity and degree of information interaction, which reflects the interaction between learning tasks and learners. In this study, there might be more information interaction among students in the 1:m group than in the 1:1 group. Therefore, students' mental load provided with ES in the 1:m group had a higher level than those in the 1:1 group. Under the condition of 1: m, group members regard the only VM as the common focus, which prompts information sharing and interactions with each other (Antle, 2014, pp. 55–56). Accordingly, a common focus helps build a shared transactional space within a group (Antle, 2014, p. 65), which benefits to produce more effective information exchange. In contrast, under the condition of 1:1, each student in the same group could operate VM individually, but it may hinder the information exchange among group members, and thus they showed a lower level of mental load. When it comes to mental effort, the time × TSR × ESA interaction for the mental effort of students was statistically significant. During the last time round (EI), when students were provided with ES, the students' mental effort in the 1:m group showed a lower level than those in the 1:1 group. However, in the 1:1 condition, the mental effort of students with ES was higher than that of students without ES. Compared with the 1:m group, ES exerted more cognitive load on group interaction in the 1:1 group (Sweller et al., 1998). Previous studies show that ES has complex effects on the cognitive load of groups, which may reduce (King, 2007) or increase the cognitive load (Dillenbourg & Jermann, 2007). This study provided evidence that this complexity could be affected by technology affordances, such as the device-student ratio and external support from instructors.

How Did the Above Effects Change Over Time?

The statistical results in this paper showed the impact of technology affordances on knowledge acquisition and cognitive load changed over time. In this study, TSR and the ESA could affect students' knowledge acquisition. More concretely, under the 1:m condition, students in groups were unfamiliar with the activities in the early period. ES could play significant guiding or prompting roles to help keep students' attention, and thus it had a significantly positive effect on knowledge acquisition in this case. In contrast, along with the inquiry process, students' familiarity and adaptability could grow. They were more familiar with certain technology affordances, so the effect of ES fade away over time. The role of ES became not so obvious in later periods. Moreover, under 1:1 condition, as students operated their own devices, there needed more attention to the adaptation of ES. Hence, it showed a negative effect of ES on students' knowledge acquisition under 1:1 condition in the middle period. During collaborative learning, there could have complex dynamics inside the interaction (Wang & Le, 2022). Familiarity and adaptability are very likely to be the moderator to influence students' perception of technology and thus affect students' knowledge acquisition.

For cognitive load, in the last round of the experiment, statistics results indicate that ES made students invest more mental effort in the condition of 1:1 than that in the condition of 1: m. While under the condition of 1:1, students with ES paid more mental effort than students without ES. One possible explanation for this difference is that more is not always better (Larrain et al., 2018). Given our research design, ES could become a new content that students need to learn, in addition to the knowledge of scientific themes. Specifically, under the 1:1 condition, it was hard for students who have little prior experience with technology to simultaneously operate screen and ES individually. In the early and middle periods, each student explored the settings of devices and ES. As their familiarity grows, they found more technology possibilities to choose to combine. But they could only face themselves. It was more likely for these students to cost more time, devote more energy and show more concerns in this late period. As described by Paas and Van Merrienboer (1994), inappropriate instructional design will lead to excessive mental efforts and harm memory retention and knowledge understanding in tasks. Our results found that aimless increment of technology input might increase students' cognitive load and in turn hinder their learning.

As mentioned before, except for time, the impact of technology affordances on knowledge acquisition and cognitive load could potentially be attributed to other differences between the conditions, such as the learning content and VMs in different learning theme. Thus, we need to treat relevant results carefully.

Implications and Limitations

As for the implications of this study, what is worth noting is that instructional designers need to think over when and how to give ES to students in different mobile device-student ratio conditions. In this study, students provided with different TSR and ESA showed different cognitive load and knowledge acquisition, which partly coincides with Jeong and Hmelo-Silver (2016)'s research, that is, students' learning processes vary due to their perceived affordance; more to the point, this study found that technology affordances have a time effect. This time effect may be related to students' familiarity and adaptability with technology. Generally, educational administrators tend to create an environment in which students in groups can have sufficient technical possibilities. Our study suggests that technologies can be friends, foes, or nothing, depending on the stage of the course. For instance, ES could help students' knowledge acquisition in the early stage. However, ES could make students invest more mental effort under the 1:1 condition, in the late period. Interestingly, ES could also have no significant effect on knowledge acquisition. Therefore, what counts is not how many technologies you use, but how to balance well the relationship between students and technology in different teaching stages.

The limitations of this study lie in three aspects. Not all students fully attended the experiment in this study because of sick leave or extra-curricular activities. Besides, the conclusions of this study may be influenced by different inquiry themes, although we carried out standardized treatment to make a horizontal comparison, especially the mental load dimension of cognitive load. Another limitation was the lack of attention to the collaborative process in groups. This leaves room to think and explore the process to provide more evidence on the explanation of how and why students' knowledge acquisition and cognitive load varied. In future work, we tend to pay more attention to diverse data and conduct a qualitative analysis of students' collaboration and cooperation when provided with different TSR and ESA.

Appendix 1 ES Before Inquiry

Clarify inquiry goals	• Read the inquiry content and steps in the worksheet, clarify the tasks and goals of inquiry
Practice and thought	• Operate VM, attentively observe the experiment phenomena, and reflect on the group inquiry's content.
Thinking aloud	• Take notes of the experiment phenomena, then take turns expressing personal ideas and opinions (please pay attention to supplementing speaker's opinions, pointing out discrepancies, and explaining your own opinion)
Integrate and perfect	• One group member (not the group leader) integrates the points mentioned during the thinking aloud process, and the other group members complement and perfect the integrated content together (When listening to others, pay attention to discovering omissions and mistakes, and ask others for explanations immediately if you don't understand)
Draw a conclusion	• Complete the group worksheet with all group members together.

Appendix 2 ES During Inquiry

The function of Inspector

- Keep the discussion from getting sidetracked
- Remind group members to follow the experiment requirements
- Manage the inquiry process and allocate time reasonably
- Facilitate all group members to participate in the collaborative inquiry

Appendix 3 Inquiry Tasks in Group Worksheets

Learning theme	Task 1	Task 2
Refraction of light (RL)	What happens when light enters the water from the air?	If change the angle of the incident light from air, what happens to the ANGLE of refraction? Find the pattern
Electrical circuits (EC)	State the function of the components in a circuit diagram by analyzing the states of switches, currents, and bulbs	Add a small bulb in a given circuit (modifying a circuit diagram) to enable the two small bulbs to light up or go out at the same time

Learning theme	Task 1	Task 2
Electromagnetic induction (EI)	Given an electromagnetic system, figure out in what situation the light goes on and try to find the pattern of the changing of brightness	Try to list some hypotheses of the relationship between the characteristics of some components in a given electromagnetic system. Test these hypotheses by observing the phenomenon in the VM by changing some settings

Appendix 4 Sample Items for Post-tests

Refraction of Light (RL)

1. When light enters the water from the air, it deflects inward. ( )
   Answer: True (T)
2. Among the following phenomena, the refraction of light is ( ).

   A The sun shone on the thick leaves and appeared light spots on the ground.
   B The diver saw the man on the shore getting taller in the water.
   C People saw "white clouds" floating in the water by the lake.
   D We can see objects that do not emit light from all directions.

   Answer: B

Electrical Circuits (EC)

1. Connect two intact small bulbs in series. When one small bulb is on, the other will be on. ( )
   Answer: True (T)
2. Which of the following description is correct? ( )

   A As long as the switch is closed, the small bulb will light up.
   B Wires can connect circuits.
   C The power supply can consume electric energy.
   D A small bulb can still glow when its filament is broken.

   Answer: B

Electromagnetic Induction (EI)

1. Placing the magnet stationary in the coil will produce an electric current. ( )
   Answer: False (F)
2. Which of the following description of the magnet is correct? ( )

   A The magnet moves in the coil of the closed circuit and the bulb emits light.
   B The magnet moves in the coil of the closed circuit without changing the voltage.
   C The magnetism of a magnet will never disappear.
   D Magnets are divided into the South Pole and the North Pole.

   Answer: A

Appendix 5 Cognitive Load Scale

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

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

Declarations

Ethical Approval All procedures performed in the study were following the ethical standards of the Research Ethics Review Committee of the Faculty of Education, Beijing Normal University.

Consent Informed Consent was obtained from all students included in the study. Data was reported anonymously in the study.

Conflict of Interest The authors declare no competing interests.

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