Title	The effects of load reduction instruction on educational outcomes: An intervention study on hands-on inquiry-based learning in science
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Abstract

Load reduction instruction (LRI) is an instructional approach designed to manage the cognitive load on students as they learn complex learning materials. According to Cognitive Load Theory, complex learning is associated with high cognitive load and when not effectively managed, could impede learning. Inquiry-based learning with hands-on component, where students conduct experiments to find solutions to problems, are known to incur high cognitive load. In this study, we examined the effects on students' educational outcomes when the five key principles of the LRI framework were implemented to reduce the cognitive load of inquiry-based learning with hands- on involvement. Multiple regression analysis was used to compare the educational outcomes of the intervention and control groups. The control group also experienced hands-on inquiry-based learning, but without LRI. Results showed that students in the intervention group had better outcomes, indicating the effectiveness of LRI in managing the high cognitive load of complex instruction.

Keywords: cognitive load theory, hands-on learning, intervention study, load reduction instruction

1. Introduction

The inquiry-based learning approach has been widely recommended for the science curriculum as it encourages students to construct their own knowledge through self-directed learning processes (National Research Council, 2015). During inquiry-based learning of science, students carry out investigative steps, which often requires “hands-on” involvement (i.e., engagement in physical manipulations), to search for solutions to science problems

presented in the learning tasks to promote in-depth understanding of science, (Bredderman, 1983). Researchers have suggested that inquiry-based learning of science helps students to: (1) integrate the scientific knowledge, science experimental skills, and develop scientific attitudes necessary for optimal science performance; (2) provide opportunities to develop and coordinate essential skills that are required for optimal science performance; and (3) eventually enable knowledge transfer to everyday life or work situations (Riga et al., 2017).

Although evidence for the benefits offered by inquiry-based learning approach with hands-on components (henceforth, "hands-on inquiry") has been well-documented in the in the science education literature, other studies generated results to the contrary (e.g., Husnaini & Chen, 2019; Stull & Mayer, 2007; Wilcox & Lewandowski, 2017). This approach has been contested by many scholars examining human cognitive architecture from a cognitive load theory viewpoint (e.g., Carlson et al., 2003). This issue has been the object of debates and discussions by many researchers in recent years (see Zhang, 2019, for a review).

To address the cognitive load issue in implementing inquiry-based learning, researchers have proposed the use of varied approaches and instructional elements (Zhang, 2019). A potentially promising approach - the "load reduction instruction" (LRI) - was introduced by Martin (2016). The LRI represents a specific combination of classical instructional models (e.g., scaffolding, guided independence) that seek to manage the cognitive load on students as they learn. Beyond its impact on knowledge transfer and student achievement, the LRI is also known to be associated with student attitudes such as academic motivation and engagement (Martin, 2016). The LRI concept is still nascent; studies that involve the LRI are largely theoretical and the empirical studies that have been done are primarily exploratory in nature. Specifically, regarding science instruction, only one study has been completed thus far (Martin et al., 2021) but is not experimental in nature. To date, there are no known intervention studies which have been conducted in the investigation of the LRI on science instruction and science

related student outcomes. The present study thus seeks to address this gap and investigate the effects of an LRI-based hands-on inquiry intervention on students' cognitive (achievement) and non-cognitive outcomes (sense of competence, interest, self-regulation, career aspirations), in the context of science instruction. The following sections lay out the foundation on which this study is based upon.

1.1. Cognitive load theory and inquiry-based learning

Cognitive load theory (CLT, Sweller, 1994), which draws on the different features and mechanisms present in human cognitive architecture, provides principles and design recommendations to enable meaningful learning with complex materials (Pollock et al., 2002; Sweller et al., 2011), such as those that are present during inquiry-based learning. CLT underscores the interactivity between the working memory (WM) and long-term memory (LTM) during learning processes (Kalyuga, 2010). WM is a cognitive structure where current and active mental processing takes place. The capacity of WM is limited and can only process a limited number of elements simultaneously (Miller, 1956); the LTM on the other hand is where vast amounts of information are stored in organized structures known as schemas (Chi et al., 1982). In the process of learning, new information needs to be integrated with existing knowledge present in the LTM schema, and all these processing occurs in the WM, which creates cognitive load (Kalyuga, 2009; Sweller et al., 2011). Learning thus occurs when information is successfully processed in the WM and moved to the LTM for storage in a process known as schema acquisition (Newell & Simon, 1972; Sweller et al., 2011).

CLT also underscores three types of cognitive load: (1) intrinsic cognitive load, which is related to the basic nature of the novel information being processed; (2) extraneous cognitive load, which is related to instructional factors that can be altered; and (3) germane cognitive load, which refers to the ratio of working memory resources devoted towards dealing with

intrinsic cognitive load to those for extraneous cognitive load (Sweller, 2010). In relation to instructional design, CLT postulates that acquisition of knowledge is optimized when germane load is maximized for the learning task--this means that more resources can be devoted towards schema acquisition from the WM to the LTM (Bannert, 2002).

The complex nature of ill-defined problems typical in inquiry-based learning places may strain the WM of learners and affect the quality of knowledge transfer towards the LTM (Schweppe & Rummer, 2014). Although inquiry-based learning encourages self- discovery and knowledge transfer through the independent exploration of ill-defined problems, it is assumed to impose a high cognitive load to the learners (Kirschner et al., 2006). From a CLT perspective, this cognitive cost stems from the general search phase during problem solving (Kadir et al., 2015, 2019; Rourke & Sweller, 2009). The need to sieve through large portions of the LTM during information retrieval processes places heavy cognitive load on the WM (Kadir et al., 2019). In inquiry-based learning, knowledge construction (vs. the borrowing and reorganizing principle characterizing direct instruction) through the independent exploration of multiple solution pathways, coupled with the vaguely specified goals of ill-defined problems, exacerbates this issue by increasing the search space and possibility of cognitive overload in the scientific learning process (Ormerod, 2005; Sweller et al., 2011). The problem is compounded when the domain of scientific knowledge encountered is new and rule automation is not sufficiently established to free up cognitive resources for the learner to devote to appropriate planning rather than to the details of legitimate moves during problem solving (Cooper & Sweller, 1987). Furthermore, inquiry-based learning with hands-on features was also regarded as creating additional extraneous cognitive load by making the learners think about a problem and doing the investigation at the same time (Stull & Mayer, 2007; Zhang, 2019). In utilizing the inquiry-based learning approach in science education, educators hence need to be acutely aware of these cognitive constraints and issues. Although adopting this

approach may promote deep understanding of a topic in learners, novice learners who lack pre-existing knowledge in the domain may become overwhelmed by the complexity of the learning tasks, resulting in impaired learning (Kadir et al., 2020; Kirschner et al., 2009; van Merriënboer & Sweller, 2005). In the planning and designing of inquiry-based learning approach, it would be prudent for educators to consider alternative ways of implementing the approach in such a way that cognitive load is effectively managed, to support schema construction and acquisition for optimal learning to take place, whilst still providing an authentic environment to promote interest and real-world problem solving in students (Kadir, 2018).

1.2. Load reduction instruction during inquiry- based learning

Martin's (2016) LRI can be utilized to promote efficient cognitive load management and facilitate the acquisition and application of complex ideas, such as that which is present during inquiry-based learning. Martin and Evans (2018) developed the LRI framework to provide a structure of instruction based on CLT for educators to implement in the classrooms. The LRI framework comprises five factors: (LR1) Difficulty Reduction, (LR2) Support and Scaffolding, (LR3) Practice, (LR4) Feedback, and (LR5) Guided Independence. In line with the LRI framework, complex concepts need to be simplified at the initial stages of learning (LRI 1; see also Mayer & Moreno, 2010) to avoid overwhelming the WM and establish base foundational knowledge first. The instructional material should also be scaffolded and designed accordingly by teachers following a simple-to-complex sequencing to acquire skills and knowledge (LRI 2; see also Renkl, 2014). The learners should also be given ample opportunities during instructional time to practice the skills and knowledge acquired to facilitate the transfer from WM to LTM (LRI 3; see also Karpicke & Blunt, 2011; Rosenshine, 2009). Additionally, receiving prompt and appropriate feedback from both teachers and peers are important because it helps students reduce extraneous cognitive load by limiting the information search and retrieval scope within the LTM in the process of completing the

learning tasks (LRI 4; see also Mayer & Moreno, 2010). The implementation of LRI 1–4 can facilitate the transfer of knowledge and skills from WM to LTM and develop the learner's fluency and automaticity in the domain (Martin & Evans, 2018). Increasing learners' level of expertise in the domain frees up WM resources to acquire new knowledge and skills, which allow for exploratory learning tasks to be incorporated into the lesson plan (Rosenshine, 2009). Once sufficient learner expertise is ascertained, the teacher can then consider implementing LRI 5, which promotes learning beyond textbook material and to provide a holistic and authentic science education through the solving of real-world problems. Instituting the final LRI 5 practices also offers the opportunity for students to hone their executive functioning and application skills when drawing connections between learned theoretical knowledge and novel real-world problems (Drigas & Karyotaki, 2019).

The LRI can be regarded as a promising approach that can generate positive effects in both cognitive (e.g., achievement) and non-cognitive domains (i.e., student attitudes; psychosocial factors) (Martin, 2016). The LRI has been shown to be positively associated with student achievement (cognitive outcome) (Martin & Evans, 2018) as well as student attitudes such as motivation and engagement (non-cognitive outcomes) (Martin et al., 2021). Additionally, Kadir (2018) has also demonstrated that effective cognitive load management has a positive relationship with sense of competence, interest, self-regulation, and career aspirations.

1.3. The present study

The study aimed to measure the effects of LRI strategies while implementing hands-on inquiry on student achievement and attitudes. By managing the cognitive load in complex science learning materials using LRI strategies, we expected benefits in the intervention group

related to student achievement (a cognitive educational outcome) and attitude (a non-cognitive educational outcome) scores.

We generated the following hypotheses about the effects of the LRI framework when applied to the hands-on inquiry-based learning approach.

> Hypothesis 1. (H1): The use of the LRI framework in implementing hands-on inquiry will improve student achievement.

The level of learning in a student can be assessed through the use of formative and summative assessments in the measurement of successful transfer, retainment, and application of learned knowledge (Mayer, 2002). Instructional methods which better facilitate these processes are expected to produce higher student achievement. In particular, LRI 1 (Difficulty reduction) and LRI 2 (Support and scaffolding) should help teachers in transferring the needed knowledge to students and facilitate the encoding of new knowledge from the WM to the LTM. LRI 3 (Practice) should promote the retainment of knowledge in the students' LTM through immediate active rehearsal. LRI 4 (Feedback) and LRI 5 (Guided independence) is postulated to improve students' achievement by aiding students in applying their learned knowledge through assisted scoping of problems and independent problem-solving.

> Hypothesis 2. (H2): The use of the LRI framework in implementing hands-on inquiry will improve intermediate learning mechanisms and regulatory processes.

In this study, we specify the cognitive domain of self-regulation, which refers to the cognitive strategies that students use to learn and monitor their understanding of learning materials (Zimmerman & Pons, 1986). Stages LRI 2 (Support and scaffolding) and LRI 4 (Feedback) in the LRI framework provide opportunities for teachers to mediate the learning process and shape students' self-regulatory processes. This is done through direct feedback (LRI 4) or role-modeling by teachers during scaffolding and providing support to students (LRI 2). Meanwhile,

LRI 5 (Guided independence) allows for students to actively use, evaluate, and adjust their learned metacognitive self-regulatory skills. In particular, in adhering to the LRI framework, structuring LRI 5 only after LRI 1–4 allows for sufficient time for teachers to actively impart self-regulatory skills to students, who in turn gain more positive impressions of its usage when its effectiveness is appropriately demonstrated during the final LRI 5 stage.

> Hypothesis 3. (H3): The use of the LRI framework in implementing hands-on inquiry will improve students' sense of competence in science.

A student's academic self-concept is also known to be a central part in student's learning (Kadir & Yeung, 2020). Academic self-concept refers to the perception that a student has about his or her own academic abilities (Marsh, 1990). Sense of competence constitutes one of the factors in a two-factor solution (competence and affect) of academic self-concept (Kadir et al., 2017). The introduction of simpler tasks at the initial stages of learning in LRI 1 (Difficulty reduction) allow students to have a higher probability of task completion which boosts their confidence in learning science. Delaying real-world problem solving till the last stage of learning at LRI 5 (Guided independence) also allows for the consistent accumulation of “small wins” which is postulated to improve students' sense of competence and achievement.

> Hypothesis 4. (H4): The use of the LRI framework in implementing hands-on inquiry will improve students' interest in science.

Besides the promotion of academic learning outcomes, hands-on inquiry-based learning also places cultivating the interest of students in the subject as one of its primary objectives. When cognitive load is managed and reduced sufficiently to cater to learner profiles in the LRI framework, learning is eased and students may start to enjoy learning science (Kadir et al., 2020). Their increased sense of competence through the successful completion of individual

learning tasks may also contribute to their interest due to the prospect of being able to do well in the subject.

Hypothesis 5. (H5): The use of LRI framework in implementing hands-on inquiry will improve students career aspirations.

Sustaining students' interest in science can lead to educational aspirations in the given domain (Yeung et al., 2010). Students who are interested in learning science are also more inclined to pursue science-related careers in the future (Deci & Ryan, 2008). If implementation of the LRI framework can increase students' predispositions towards science-related jobs, then the theoretical underpinnings of the instructional processes could be applied across various science disciplines to address declining enrolments and other issues surrounding science education (Kadir, 2018).

In summary, we hypothesized that (1) the intervention group would have better educational outcomes than the control group in terms of their achievement scores and attitudes (i.e., sense of competence, interest, self-regulation, and career aspiration), and since the LRI intervention primarily targets the cognitive aspects of learning, we hypothesized that the (2) cognitive intervention effects (i.e., student achievement) will be stronger than the non-cognitive ones (i.e., changes in student attitudes towards the domain of science).

2. Method

2.1. Participants

The participants in this study were four Grade 7 science teachers (2 males; 2 females; age M = 35.0 years) and 156 Grade 7 students (83 boys and 73 girls; age M = 13.1 years) nested in four classes from a school in Singapore in a high socio-economic area. Two of the teachers (1 male and 1 female) volunteered to be involved in the intervention and attended the training workshop organized by the researchers, so their two science classes (n = 75) were assigned to

the intervention group. The two science classes taught by the other teachers were assigned to the control group. All science teachers had engineering degrees and had completed a year of teacher training (specializing in science and mathematics curriculum) at the National Institute of Education in Singapore prior to their teaching career. They had at least 5 years of science teaching experience in a secondary school. Random lesson observations were conducted for science lessons taught by each teacher in the intervention and control groups and field notes were taken to record the similarities and differences among the teachers and also for the purpose of intervention validity. English is the medium of instruction in all Singapore schools, so both science topics were taught in English. All participants in the intervention and control conditions were fluent in the English language and of high academic ability but were considered novices in the learning of the scientific concepts of the topics Speed and Density.

2.2. The intervention and control groups

During the period of the study, students in the intervention and control groups engaged in hands-on inquiry by carrying out activities or experiments to solve scientific problems in the topics of speed and density but only the intervention group followed the LRI framework. All participants engaged in lessons on Speed followed by Density. Students in both groups were given instructional worksheets to explain their learning tasks and were expected to work collaboratively in groups of four to carry out the hands-on scientific investigations, record their processes and findings, and draw conclusions. In the science education literature, such instruction is also known as ‘physics by inquiry’ (McDermott et al., 1996), hands-on scientific discovery or inquiry-based learning (Hardy et al., 2006; Kadir et al., 2020). The activities were similar to those reported by Kadir et al. (2020) and Hardy et al. (2006), which are known to help students make sense of scientific principles. Examples of problems in Speed include finding out the speed of metal balls rolling down ramps and the variables affecting the changes and examples of problems in Density include investigating the densities of objects which float

and sink in different types of liquids. The lessons were prepared collaboratively by the teachers in the participating school and the researchers in the study.

After preparing the lessons, efforts were made to differentiate the intervention group from the control group. For the intervention group, the lessons were designed in such a way that the instruction or method of delivery and learning materials followed the LRI framework closely (LRI 1: Difficulty Reduction, LRI 2: Support and Scaffolding, LRI 3: Practice, LRI 4: Feedback, and LRI 5: Guided Independence). Meanwhile, whilst the control group engaged in hands-on scientific investigations, unlike the intervention group, the teachers of the control group were not trained in the LRI method and were told to strictly follow inquiry-based science learning processes. However, they were not told to hold back any standard instructional practices, so as not to put the control group at a disadvantage. Both the lessons of the intervention and control groups were recorded, and the researchers were present to collect field notes to record the similarities and differences of the groups. The similarities and differences of the two groups are provided in Table 1 and are grouped according to the five LRI principles based on the analyses of video recordings of the lessons and lesson observations conducted by the researchers.

Basically, students in the intervention group started with simpler tasks (i.e., LRI 1: Difficulty Reduction) before being introduced to the open-ended ones. In contrast, students in the control group were given the open-ended tasks to work on right at the beginning of the lessons, which incurred high cognitive load due to their lack of schemas as novices. Students in the intervention group were given a high level of teacher support and scaffolding (i.e., LRI 2: Support and Scaffolding). In contrast, the control group students engaged in independent learning with minimal teacher facilitation or guiding questions. Therefore, the control group students' frequent search for information and feelings of insecurity in getting their scientific processes and answers right tended to incur high extraneous cognitive load. As for practice

TABLE 1 Learning experiences of the intervention and control groups

Features of LRI framework	Learning experiences	
	Intervention condition	**Control condition**
LRI 1: Difficulty reduction	Both groups of students carried out hands-on scientific investigations to solve problems in Speed and Density topics.	
	Level of difficulty was increased in stages Simpler tasks were introduced at the initial stages of learning and guided inquiry tasks were implemented at the later stages.	Level of difficulty was high for each lesson Complex inquiry-based learning tasks were implemented for all the lessons.
LRI 2: Support and scaffolding	Both groups of students were given worksheets to guide the learning experiences and worked collaboratively in groups of 4 with their teachers as facilitators, thus both groups received peer support.	
	High level of support: More facilitation Support was given through teacher facilitation; Explicit input were also provided by the teachers verbally or via information sheets to support student learning whenever needed.	Low level of support: Less facilitation Support was given through random facilitation by teachers when called for by students, but independent learning was encouraged. Neither explicit input nor direct teaching was conducted by the teachers.
	More scaffolding Worksheets were designed using a simple-to-complex sequencing, with complex tasks introduced after the simpler tasks were accomplished. Guiding questions and answer options were provided to help students draw conclusions from their investigations.	Less scaffolding Worksheets were designed such that students were required to find solutions to open-ended questions by carrying out scientific investigations and explaining the phenomena observed. There were no guiding questions and answer options to guide students.
LRI 3: Practice	Both groups of students completed one page of practice questions available in their science textbook at the end of the topic chapter, to reinforce what they have learned during the lessons.	
	More practice Students completed additional practice questions after every hands-on task, in addition to the textbook ones, as homework.	Less practice The practice questions done by the students were restricted to the ones found in their textbooks.
LRI 4: Feedback	Both groups received teacher feedback during group facilitation.	
	More feedback given to students Feedback was given at regular intervals to ensure that students were confident that they are on the right track. Due to time and manpower constraints, these are conducted as a class at times. For those who are lost or gone off track, teachers will promptly guide them back on track with guiding questions and direct teaching.	Less feedback given to students Feedback was given sparingly in order to encourage the students to figure out solutions on their own and not to rely on the teachers for answers. Guiding questions were given to those who were lost or gone off-track, without explicitly telling them the answers and whether they were right or wrong.
LRI 5: Guided independence	Both groups experienced independent learning at different stages.	
	Learning was closely guided before independent learning Students experienced independent learning at the final lesson of each topic, after accomplishing the simpler tasks which were closely guided by facilitators.	Independent learning Students experienced independent learning at every lesson, where they are expected to figure out solutions to science problems on their own without being told what to do.

(i.e., LRI 3: Practice), both groups completed practice questions on the topics, with the invention group completing additional ones as homework. Practice helps to form schemas which reduce the cognitive load resulting from complex tasks. Due to the close supervision and higher facilitation of students in the intervention group, they received more feedback (LRI 4: Feedback) at regular intervals than the control group. The control group was given less feedback to reduce the dependency on teachers for answers even at the beginning stages of learning, so the lack of affirmation could have increased the cognitive load experienced by the control group. After the students in the intervention group had established the baseline knowledge, they were encouraged to try out more complex tasks independently with less guidance by teachers (LRI 5: Guided Independence). Unlike the intervention group, the control group was encouraged to learn independently through all the lessons.

2.3. Procedure

Lessons were delivered by the science teachers and all data were collected by the teachers during school curriculum hours. Fieldnotes were collected by the researchers as observers. The study consisted of four phases: (1) pre-intervention phase, (2) teacher knowledge acquisition phase, (3) students' knowledge and skills acquisition phase, and (4) post-intervention phase. Each phase was conducted within the school premises during the first school semester in the first half of the year.

2.3.1. Phase 1: Pre-intervention phase

Students in both the intervention and control groups completed a Prior Knowledge test (i.e., pre-test) on Speed and Density to measure their existing knowledge of the topic. The Prior Knowledge tests were designed by the research team, based on the curriculum objectives of the topic determined by the school, after which it was given to the science teachers in the school for review and moderation. The Speed questions mainly assessed

students' understanding of distance, time and average speed whereas the Density questions mainly assessed students' understanding of floating and sinking, and ideas on relative density, given certain scenarios. During this phase, students also completed an Attitude pre-test to measure their attitudes towards science before learning the science topics of Speed and Density.

2.3.2. Phase 2: Teacher knowledge acquisition phase

Science teachers in the intervention group attended five 1-h workshops conducted by a research team member after school curriculum hours. During the first workshop, they were introduced to information about students' cognitive processes during learning, what LRI is about, and how to use LRI to design the lessons. In subsequent workshops, teachers worked with the researchers to prepare the intervention materials and lesson design using the five factors in the LRI framework: LRI1: Difficulty Reduction, LRI2: Support and Scaffolding, LRI3: Practice, LRI4: Feedback, and LRI5: Guided Independence. More specifically, the teachers learned to design instruction in stages, introducing simple concepts prior to more complex ones to meet students' learning needs (LRI 1, 2 and 5), design practice questions as homework for practice (LRI 3), and how to facilitate group learning and discussions and provide timely feedback (LRI 4).

2.3.3. Phase 3: Students' knowledge acquisition phase

Students in both the intervention and control groups engaged in hands-on learning during their science lessons on Speed and Density. Instructional materials from Kadir et al. (2011) were used as a reference for the topic of Speed and Wong et al. (2011) for the topic of Density. Firstly, teachers in the control group prepared lesson plans and instructional materials on Speed and Density for the control group, using the inquiry-based instructional method. The method requires students to solve open-ended problems and they need to carry

out hands-on activities to find solutions to the problem while clearly describing the processes they undertook. These were then provided to the intervention group teachers and researchers for the application of the five factors of LRI. Both groups took 15 h over 6 weeks to learn both topics of Speed and Density (i.e., 7.5 h over 3 weeks for each topic) and covered the same concepts. Although the control group teachers were unaware of the features of the intervention, researchers observed some features implemented in the control group lessons which were similar to the intervention group and had recorded them. Table 1 describes the lesson features and differences between the intervention and control groups.

2.3.4. Phase 4: Post-intervention phase

After learning each topic, students completed a Knowledge Transfer test to assess their understanding of the topic. An Attitude post-test measuring student attitudes towards science after the learning of the topics Speed and Density was administered after the intervention phase.

2.4. Intervention fidelity

To evaluate the extent to which the intervention was implemented as planned, we focused on four key elements of intervention fidelity: teacher intervention workshops for teachers, intervention delivery, intervention receipt, and intervention enactment (cf., Smith et al., 2007). Lesson observations in the intervention condition indicated that teachers adhered to the co-designed lesson plans and followed the teacher manual. They were able to administer the lessons within the stipulated timeframe. Lesson observations in the control condition indicated that the teachers were teaching in the same way as the inquiry-based lesson plans and matched the description in Table 1. Teacher workshops were delivered by the first author of this paper, as she had previous experience in delivering professional development programs for science teachers. Both teachers in the intervention condition

attended all the workshops at the same time to ensure systematic delivery, and to maximize the fidelity of intervention delivery. Additionally, the first author was stationed in the school during the period of intervention delivery, so that teachers could readily consult about the intervention. She also met with the teachers in the intervention condition twice a week for a discussion to reflect on the intervention delivery, to ensure understanding of the intervention, and to answer any questions. To evaluate the intervention enactment, video recordings of the lessons were viewed and checked against the lesson plans and teacher manual by the research team. There were no significant deviations from the procedures.

2.5. Materials and measures

The materials used in the study comprise knowledge tests to measure student achievement and survey questionnaires to measure student attitudes towards science. The knowledge tests were adapted from Kadir et al. (2011) and Wong et al. (2011) and reviewed by the science department in the school as well as the researchers in this study. The survey instrument was adapted from measures with acceptable reliability and supported with robust evidence of validity.

2.5.1. Prior knowledge and knowledge transfer tests

Student achievement was assessed by comparing the Prior Knowledge (i.e., pre-test) and Knowledge Transfer (i.e., post-test) scores. Prior Knowledge test assessed students' conceptual understanding before the science lessons on the topic were delivered and Knowledge Transfer test assessed students' conceptual understanding after all the science lessons on the topic were delivered (i.e., their ability to transfer the knowledge acquired during the lessons to answer questions). Each paper-and-pencil (i.e., written) test comprising 10 questions was assigned 10 marks - one mark would be awarded for the correct answer to each question and no mark would be awarded when the question was incorrectly answered.

The Prior Knowledge and Knowledge Transfer tests were not identical, but covered similar concepts, with the Knowledge Transfer test assessing concepts taught during the instruction. Therefore, the Knowledge Transfer test was of higher complexity than the Prior Knowledge test. The teachers and a researcher marked each student's test separately. They had an inter-rater agreement of 100%. Comparisons were made between the intervention and control groups for each topic.

2.5.2. Attitude in science survey

Student attitudes towards Science were measured by a survey questionnaire in which students rated each item on a scale of 1 (strongly disagree) to 6 (strongly agree). The appendix presents all the items used in the self-report survey. Due to the domain specificity nature of attitudes, all items were related to the science domain (Yeung et al., 2010). The pre-test survey was administered prior to the learning of the topics and the same survey questionnaire with identical items was administered again after both topics were taught (post-test). Comparisons were made between the intervention and control groups.

2.5.3. Sense of competence

Four items were used to measure the students' sense of competence in science (e.g., “I have always done well in science”). The statements were taken from the self-concept scale in Kadir et al. (2017) who adapted the items from the Marsh (1992) Academic Self-Description Questionnaire (ASDQ) instrument. In the study, this factor had reliabilities of 0.92 and 0.94 for pre-test and post-test, respectively.

2.5.4. Interest

Student interest is a factor adapted from the affective component of academic self-concept (Marsh et al., 1999). Interest was measured by four items (e.g., “I find science

interesting"), taken from Kadir et al. (2017) who adapted the scale from the study by Marsh et al. (1999). In the study, this factor had reliabilities of 0.86 and 0.87 for pre-test and post-test, respectively.

2.5.5. Self-regulation

Self-regulation was measured by four items (e.g., "When I'm reading my science materials and do not understand something, I stop and think it over"), adapted from the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich & de Groot, 1990). In the study, this factor had reliabilities of 0.83 and 0.86 for pre-test and post-test, respectively.

2.5.6. Career aspiration

Career Aspiration was measured by four items (e.g., "I want to have a job that has to do with science"), adapted from Yeung et al. (2011). In the study, this factor had reliabilities of 0.91 and 0.87 for pre-test and post-test, respectively.

2.6. Statistical analysis

The statistical analysis for the study was designed to investigate the effects of the intervention by comparing the 'growth' of two groups of students (i.e., intervention and control groups) in terms of their achievement and attitudes towards science, following learning in two complex science topics: Speed and Density. In the study, we calculated the mean scores and estimated two regression models for each of the two achievement variables and four attitude factors.

TABLE 2 Descriptive statistics and bivariate correlations for the measured student attitude variables of the study at pre-test

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 Com1	-															
2 Com2	0.77***	-														
3 Com3	0.77***	0.78***	-													
4 Com4	0.73***	0.68***	0.71***	-												
5 Int1	0.42***	0.43***	0.38***	0.38***	-											
6 Int2	0.35***	0.35***	0.33***	0.37***	0.68***	-										
7 Int3	0.31***	0.37***	0.26***	0.38***	0.59***	0.59***	-									
8 Int4	0.42***	0.41***	0.32***	0.44***	0.60***	0.61***	0.59***	-								
9 Sre1	0.26***	0.34***	0.29***	0.35***	0.22**	0.31***	0.34***	0.32***	-							
10 Sre2	0.40***	0.40***	0.38***	0.35***	0.29***	0.38***	0.31***	0.28***	0.56***	-						
11 Sre3	0.35***	0.41***	0.41***	0.34***	0.26***	0.28***	0.29***	0.29***	0.55***	0.63***	-					
12 Sre4	0.44***	0.49***	0.49***	0.41***	0.38***	0.35***	0.29***	0.37***	0.52***	0.53***	0.59***	-				
13 Caa1	0.38***	0.41***	0.36***	0.42***	0.55***	0.56***	0.47***	0.52***	0.24***	0.29***	0.27***	0.33***	-			
14 Caa2	0.44***	0.45***	0.38***	0.47***	0.59***	0.58***	0.54***	0.58***	0.27***	0.29***	0.25***	0.33***	0.86***	-		
15 Caa3	0.37***	0.34***	0.21**	0.33***	0.52***	0.50***	0.51***	0.52***	0.22***	0.22***	0.21***	0.25***	0.64***	0.75***	-	
16 Caa4	0.41***	0.39***	0.34***	0.41***	0.49***	0.53***	0.53***	0.53***	0.34***	0.36***	0.24**	0.31***	0.68***	0.75***	0.72***	-
Mean	4.49	4.50	4.46	4.60	4.84	4.88	4.94	4.94	4.49	4.97	4.96	4.93	4.56	4.40	4.36	4.00
SD	0.97	0.88	1.09	0.96	0.96	0.93	0.91	0.99	1.01	0.82	0.81	0.86	1.21	1.23	1.22	1.45

Note: $N = 156$; All variables were measured on a 1–6 Likert scale; Com1-4 = Sense of Competence variables 1 to 4; Int1-4 = Interest variables 1 to 4; Sre1-4 = Self-Regulation variables 1 to 4; Caa1-4 = Career Aspiration variables 1 to 4; $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

All variables were standardized before running the analyses. In Model 1, we predicted students' achievement and attitudes at post-test by group. In Model 2, we added students' pre-test scores and gender as predictors to control for pre-existing differences and for the uneven distribution of boys and girls between groups. We calculated R2 as a measure of explained variance. Finally, we accounted for the non-independence of the observations by adjusting the standard errors using the sandwich estimator implemented in Mplus V7 (Muthén & Muthén, 1998–2015). According to Hedges (2007), standardized mean differences (i.e., the differences in means of two comparison groups divided by the standard deviation) represent effect sizes. As the standardization of all continuous variables were done before running the analyses, the regression coefficients β of the dichotomous variables (i.e., groups and gender) represented the standardized mean differences. Therefore, the effects of the intervention condition compared to the control group could be interpreted as effect sizes (Hedges, 2007).

TABLE 3 Correlations for student attitude factors at pre-test

Variable	1	2	3	4
1 Sense of Competence	-			
2 Interest	0.54***	-		
3 Self-Regulation	0.59***	0.52***	-	
4 Career Aspiration	0.52***	0.77***	0.41***	-

Note: N = 156; All variables were measured on a 1-6 Likert scale. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

TABLE 4 Descriptive statistics for achievement and attitude measures at pre- and post-test for groups

Cognitive and attitude measures			Control group n = 81 Mean (SD)	Intervention group n = 75 Mean (SD)
Pre-test	Achievement			
		Speed	2.63 (1.09)	2.16 (1.14)
		Density	2.47 (1.09)	2.04 (1.07)
	Attitude			
		Sense of Competence	4.40 (0.85)	4.19 (1.05)
		Interest	4.92 (0.79)	4.76 (0.89)
		Self-Regulation	4.94 (0.56)	4.92 (0.80)
		Career aspiration	4.36 (0.95)	4.27 (1.19)
Post-test	Achievement			
		Speed	4.95 (1.61)	7.83 (1.25)
		Density	5.36 (1.49)	7.87 (1.31)
	Attitude			
		Sense of competence	3.47 (0.85)	4.36 (0.72)
		Interest	4.36 (0.81)	4.55 (0.70)
		Self-regulation	4.43 (0.65)	4.56 (0.75)
		Career aspiration	3.73 (0.77)	3.91 (1.11)

3 Results

3.1. Descriptive statistics

Table 2 provides an overview of the descriptive statistics and bivariate correlations of all 16 item variables in the Attitude pre-test, for all participants. The means of the variables ranged from 4.00 to 4.97. Correlations between attitude variables within the same factors were all positive and statistically significant ($p < .001$), ranging from 0.21 to 0.86. Positive and statistically significant correlations were also observed across the four attitude factors (i.e., Sense of Competence, Interest, Self-Regulation, and Career Aspiration), with lower correlation coefficients (Table 3). The highest correlation coefficient was found between

Interest and Career Aspiration ($r = 0.77$, $p < .001$) and the lowest was between Self-Regulation and Career Aspiration ($r = 0.41$, $p < .001$).

3.2. Comparisons between the intervention and control groups

Table 4 shows the comparisons between the intervention and control groups in terms of descriptive statistics for the four attitude factors and two achievement variables at both pre-test and post-test by group. The mean Prior Knowledge test scores for Speed and Density ranged from 2.04 to 2.63 out of the full marks of 10. The low scores demonstrate that both groups had low pre-existing knowledge in both science topics, prior to instruction. Higher means were observed in the Knowledge Transfer test for both groups of students for each topic, that is, 4.95 (speed) and 5.36 (density) for the control group and 7.83 (speed) and 7.87 (density) for the intervention group. Means for the attitude variables for both groups of students were generally lower in the post-test than the pre-test, except for Sense of Competence of the intervention group. This finding is in line with existing research, which shows declining student attitudes towards learning in adolescents (Kadir, 2018; Marsh, 1989; Ryan & Patrick, 2001). Further statistical analyses were carried out with multiple regression models.

3.3. Multiple regression models

Results from the two multiple regression models (i.e., Model 1 and Model 2) for each of the six outcome variables are presented in Table 5. The results showed intervention effects on student achievement in Speed, and Density, as well as student Sense of Competence, Interest, Self-regulation, and Career Aspiration.

TABLE 5 Results from multiple regression analyses

Predictors	Speed				Density			
Model	1		2		1		2	
	β	SE	β	SE	B	SE	β	SE
Groups	.71***	.04	.81***	.03	.67***	.04	.79***	.04
Gender			.03	.04			.02	.04
Pre-test			.49***	.06			.61***	.04
R^2	.50		.73		.45		.80	
	Sense of competence				Interest			
	1		2		1		2	
	β	SE	β	SE	B	SE	β	SE
Groups	.49***	.07	.51***	.06	.12	.08	.15*	.07
Gender			.01	.07			.04	.08
Pre-test			.18*	.07			.30***	.08
R^2	.24		.27		.02		.11	
	Self-regulation				Career aspiration			
	1		2		1		2	
	β	SE	β	SE	B	SE	β	SE
Groups	.09	.08	.10	.07	.10	.08	.09	.07
Gender			.01	.07			.29***	.07
Pre-test			.56***	.06			.32***	.09
R^2	.01		.33		.01		.25	

Note: Groups were coded: 1 = students who experienced intervention for topics Speed and Density, 0 = students in the control group who did not experience any intervention; gender was coded: 1 = male, 0 = female; *$p < .05$, **$p < .01$, ***$p < .001$.

3.3.1. Intervention effects on student achievement

The results support Hypothesis 1 (see Table 5). We found statistically significant positive effects of the intervention on students' achievement based on their Knowledge Transfer tests in Speed ($\beta = 0.71$, $p < .001$) and Density ($\beta = 0.67$, $p < .001$) in Model 1. The statistically significant positive effects of the intervention remain strong in Model 2 for both topics, with large effect sizes: Speed ($\beta = 0.81$, $p < .001$) and Density ($\beta = 0.79$, $p < .001$) in the Knowledge Transfer tests, after controlling for gender and pre-test (Prior Knowledge test) scores. The results indicated that students in the intervention group had higher achievement in Speed and Density than the control group, after instruction. As shown in Table 5, compared to attitude variables, a comparably large amount of variance was explained by Speed and Density in the Knowledge Transfer tests (R2 = 0.50 and R2 = 0.45 in Model 1, and R2 = 0.73 and R2 = 0.80 in Model 2 that controlled for gender and pre-test effects, respectively).

3.3.2. Intervention effects on student achievement

The intervention group had higher scores than the control group on only two of the attitude variables, thereby supporting H3 and H4 but not H2 and H5. As displayed in Table 5 in Model 2 (controlling for gender and pre-test), statistically significant positive intervention effects were found in students' Sense of Competence ($\beta = 0.51$, $p < 0.001$) and Interest ($\beta = 0.15$, $p < 0.05$). No significant differences were found between groups in Self-Regulation and Career Aspiration. A relatively large amount of variance was explained by Sense of Competence in Model 1 ($R2 = 0.24$) and in Model 2 ($R2 = 0.27$) rather than by Interest ($R2 = 0.02$ in Model 1 and $R2 = 0.11$ in Model 2, respectively). Gender effects were generally small, except for Career Aspiration ($\beta = 0.29$, $p < 0.01$) whereas pre-test was a positively significant predictor of student attitudes in all four attitude variables.

4. Discussion

The results supported three out of our five hypotheses. The intervention group was found to have higher achievement, a more positive sense of competence, and a greater interest compared to the control group, although the effect size for interest was small ($\beta = .15$) and only significant after controlling for pre-test. There was no significant difference found between the intervention and control groups in terms of other non-cognitive outcomes (self- regulation and career aspiration). If cognitive load is effectively managed for students - as had been the case in this study - then the transfer of information from WM to LTM had been facilitated, making complex learning more manageable and more appealing for the students in the long run, resulting in higher achievement (Kadir, 2018; Sweller et al., 2011). When LRI principles were implemented to support students in their hands-on learning, they developed a higher sense of competence, which could have led to higher achievement in the domain (Kadir et al., 2020). The results are in line with the findings of Martin and Evans

(2018).

4.1. Effects of LRI on student achievement

As hypothesized, the students in the intervention group had significantly higher achievement than those in the control condition, in both topics of Speed and Density. This finding provides evidence as to the effectiveness of the intervention in terms of improving achievement. The finding that students perform better when teachers implement LRI is consistent with prior research (e.g., Martin et al., 2021). It is also consistent with the proposition that when learning tasks are sequenced in gradual increments of complexity for students lacking pre-existing knowledge, learning is more effectively facilitated, resulting in higher achievement compared to learning in environments where cognitive load is not effectively managed (Blayney et al., 2010; Gerjets et al., 2006; Kadir et al., 2020). A possible explanation for this is that the LRI framework could have prevented or reduced the anticipated increase in extraneous load that other researchers (Stull & Mayer, 2007; Zhang, 2019) associate with the discovery-based and hands-on nature of the inquiry-based learning activity, which then helped the students benefit from it.

4.2. Effects of LRI on student attitudes

Apart from achievement, students in the intervention group also developed a higher sense of competence than the control group. This finding supports our hypothesis. Research has shown that achievement predicts students' sense of competence (Kadir et al., 2017; Kadir & Yeung, 2020; Marsh & Craven, 2006). When students achieve well in a curriculum domain, it builds up their academic self-concept for successful learning in the domain, and therefore they have an enhanced sense of competence. LRI may have enhanced students' sense of competence as it gradually increases the level of complexity after students have

mastered simpler concepts, so students are not overwhelmed by complex learning. The results also showed higher interest in science in the intervention group than the control group (in Model 2, after controlling for pre-test and gender), although the effect size was small. This could be attributed to the use of structured hands-on inquiry learning tasks, which the students could relate to, although more research would be required to affirm this possibility. The results showing no significant difference between groups in the other attitude factors (self-regulation and career aspiration) may imply that LRI alone may not be effective in influencing students' long-term educational outcomes. A general pattern found in these variables was that even though the descriptive statistics showed high values for most attitude factors, there was a decreasing trend from pre- to post-test for both groups. This trend echoes past research which showed the decline in student attitudes towards learning as students progress to secondary school (Marsh, 1989; Ryan & Patrick, 2001). However, the results showing that the intervention group has significantly better attitudes for two factors at post-test (after controlling for pre-test and gender differences) implies that the intervention has reduced the decline in student attitudes and could possibly change it into an upward trend if implemented consistently across all lessons.

This intervention study adds to the literature in that the five LRI principles are applicable to and can be implemented to help students manage the high cognitive load in hands-on inquiry lessons. Although we could not rule out the possibility that gender differences or pre-existing differences within some factors potentially accounted for the results, this possibility was reduced by the analysis, which controlled for gender and students' pre-test scores on each outcome measure. The analytical approach increased the internal validity of the intervention effects detected in this study. Thus, the results supported the conclusion that managing cognitive load in complex learning using LRI principles has a

positive impact on educational outcomes such as student achievement and their sense of competence, and to a small extent, their interest in the domain.

4.3. Implications for teaching and learning

There has been an ongoing tussle between researchers who advocate predominantly inquiry-based learning and those who advocate predominantly direct/explicit instructional approaches (Tobias & Duffy, 2009). According to Martin (2016, p.10), seeing the two approaches as "mutually exclusive or incompatible is to set in place a false dichotomy". Teachers who use explicit/direct pedagogical approaches only, even at the later stages of learning the concepts, would be depriving students of the chance to apply their acquired skills and knowledge in novel and creative ways, thus not optimizing the students' potential (Kalyuga, 2007). Similarly, it would not be reasonable to expect students to solve novel problems through inquiry-based pedagogical approaches at the beginning stages of students' learning when they have not been given enough opportunities to develop their basic understanding of the knowledge and skills in the domain (Sweller et al., 2011). The LRI framework provides a balance between the two approaches. In the LRI framework, the constructivist approach could be considered (i.e., LR5: Independent learning) after students have acquired the necessary skills and knowledge in the LTM (developed over time through LRI1-4), as that would free up WM resources for the students to engage in learning tasks of higher complexity (Martin, 2016).

The features of the intervention could also be implemented in other domains of the school curriculum – not just science. In this study, WM capacity could have been optimized by managing the cognitive load in complex inquiry-based learning using five LRI strategies which have been shown to be effective. Working in unison, the five LRI strategies staggered and sequenced cognitive load to free up WM space to facilitate learning. This process enables novices to effectively manage cognitive load when solving more complex problems, as they

progress in their journey to become experts in the domain. To facilitate expertise, lessons should be designed with the purpose of optimizing the positive effects of information transfer from the WM to LTM (Sweller et al., 2011).

Instruction for novices needs to be purposefully designed, beginning with simple learning tasks (LRI1: Difficulty Reduction) and should follow simple-to-complex sequencing, with support from teachers and peers (LRI2: Support and Scaffolding). Teachers should provide opportunities for students to practice what they have learned (LRI3: Practice) and regular feedback should be given (LRI4: Feedback) to reinforce what they have learned and to ensure that simpler concepts are mastered before moving on to more complex ones. Finally, when teachers are confident that students have possessed the requisite knowledge and skills in the subject domain, learning opportunities should be provided for the students to apply the knowledge and skills they have acquired to solve interesting problems in order to stretch and optimize their potential and develop expertise and interest in the subject domain. To improve learning effectiveness and efficiency and to capitalize on recent developments in CLT in education, we recommend that teachers consider implementing the five LRI principles to manage the cognitive load in complex instruction, to free up the limited WM capacity for cognitive processing and facilitate the transfer of knowledge to LTM. Implementing LRI may prevent or reduce the potential constraining effect in the hands-on and discovery features of inquiry-based learning (based on Zhang, 2019), and scaffold learning in stages for students to learn more effectively, in line with cognitive load theory.

4.4. Limitations and future research

One main limitation is with regard to the short intervention period. With a short intervention period, it is difficult to rule out the novelty impact of the intervention which could inflate student interest. However, the significant effects found within such a short intervention are promising. Future studies should extend the intervention period to beyond 6

weeks to more effectively measure the long-term impact on student achievement and attitudes. Measurements of achievement and attitudes could be taken at more regular intervals within the intervention period for researchers to study if the results are consistent. Also, a delayed post-test is absent in this study and should be considered in future studies. Some variables like career aspiration, takes time to influence. A delayed post-test could also show if the effects wear off over time or is sustained.

In addition, we did not have subjective measures of the five LRI factors from the students' perspectives using the newly conceptualized validated LRI scale (LRIS) developed by Martin and Evans (2018). Perspectives of teachers and researchers were taken on whether the five LRI factors were present in the lessons and students' perspectives of the five LRI factors were taken from selected students during the focus group interviews. Although this is a logical and defensible methodology, future validation should consider additional approaches such as self-reported survey data from students using the LRIS. The use of LRIS will facilitate the measurement of the extent of how each LRI factor is implemented in the lessons and the effectiveness of each LRI factor in contributing to student achievement and attitudes.

Finally, although not practicable within an ecologically valid setting, the effects of the LRI framework on cognitive load, WM and LTM needs to be investigated in order to have an in-depth understanding of the interactions that the LRI framework have with learner's cognitive architecture in impacting his or her learning experience. The present investigation focuses on the practicable application of the LRI framework in the setting of a science classroom environment. Future research should redirect attention towards exploring the theoretical postulations made regarding the internal mechanisms and measure cognitive load directly using eye-tracking devices (Krejtz et al., 2018) and equivalent measurements to

definitively establish the relationship between the LRI framework, cognitive load, WM, and LTM.

5. Conclusion

Hands-on inquiry-based learning is advocated in the science curriculum but known to be complex for young students who lack the necessary conceptual knowledge and skills. The findings of this study demonstrate that students in the intervention group benefitted in terms of both actual competence (achievement scores) and sense of competence when the high cognitive load associated with their hands-on inquiry experiences were managed through the implementation of the five LRI principles. Generally, learning something new is complex for novice learners and teachers should consider strategies to manage complex learning. Implementing the five principles of LRI in the design and implementation of lessons could manage the high cognitive load associated with the complexity of learning for novice learners.

EDUCATIONAL IMPACT AND IMPLICATIONS STATEMENT

The results of a 6-week study with 156 Grade 7 students in 4 science classes (2 classes in the intervention group and 2 classes in the control group) suggested that students in the intervention group benefitted from the load reduction strategies implemented in the hands-on lessons of science topics, Speed and Density. Students in the intervention group outperformed their peers in the control group in terms of achievement in the Speed and Density Knowledge Transfer tests as well as in their sense of competence in science. Results suggest the importance of managing the complexity of learning using load reduction strategies which has shown to improve students' cognitive outcomes. To further improve students' attitudes, future studies could look into training teachers to implement specific strategies which are directly aimed at nurturing student attitudes towards learning.

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CONFLICT OF INTEREST STATEMENT

We, the authors of this manuscript, have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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