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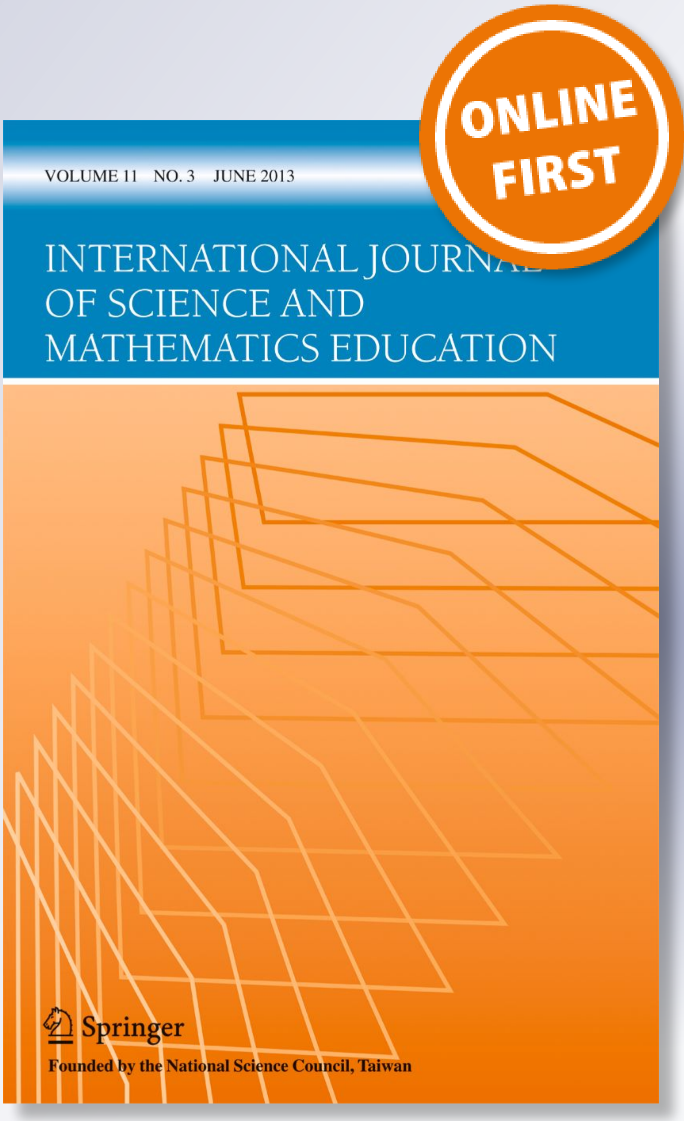

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Situated Simulation-Based Learning Environment to Improve Proportional Reasoning in Nursing Students

Ilana Dubovi [1,2] **· Sharona T. Levy** [1] **· Efrat Dagan** [2]

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Abstract Proportional reasoning is the basis for most medication calculation processes and is fundamental for high-quality care and patient safety. We designed a simulated Medication Mathematics (siMMath) environment to support proportional reasoning in transitioning via concreteness fading between two mediators. The first mediator is simulated nursing tools of medication preparation. The second is a ratio-table setup which is used as a goal representation, which enables one to spatially hold in place different quantities in their relative proportion. We conducted a two-part study with nursing students. Part 1 was a quasi-experimental pretest–intervention–posttest design assessing the effectiveness of learning, by evaluating four categories of medical calculation questionnaire items (solid medications, unit conversion, concentrations, infusion rates). We used the Noelting proportional reasoning test to evaluate the generalizability and abstraction of proportional reasoning. Part 1 included an experimental group (n = 96) learning with siMMath, and a comparison group (n = 73) learning with an equation-based lecture approach. Part 2 employed a case study design to characterize the learning process. The experimental group's learning gains were significantly higher than the comparison group's for the two most challenging categories of the medication calculation problems questionnaire, namely concentrations and infusion rates. Furthermore, the experimental group's learning gains were significantly higher than the comparison group's for formal operational reasoning on the Noelting test. Students who used a ratio-table setup scored significantly higher on the Noelting posttest questionnaire. Nursing students who learned with the siMMath environment overcame difficulties in

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proportional reasoning to the highest levels and extended this understanding to other contexts.

Keywords Concreteness fading · Medication calculation · Proportional reasoning · Simulations · Situated learning

Introduction

The concepts of ratio and proportion span the entire curriculum from elementary school through university and are fundamental to many professions and daily activities. However, ample evidence points to difficulties in proportional reasoning in adults. Therefore, our paper shows how learning with digital math simulations can serve as *situated abstractions* (a concept developed by Noss & Hoyles, 1996), to support the learning of proportional reasoning and the ratio concept.

Proportional reasoning plays an important role in many professions, such as nursing. Every nurse administers an average of 10 medication doses per hospital patient each day (Aspden, Wolcott, Bootman & Cronenwett, 2007). Evidently, there are deficiencies in nurses' medication calculation skills. Studies of qualified registered nurses have reported high levels of error related to ratio and proportional reasoning when calculating dosages. The Committee on Identifying and Preventing Medication Errors reported that at least 1.5 million preventable medication errors and adverse drug events occur each year in the USA (Aspden et al., 2007). On average, a hospitalized patient is subjected to more than one medication error each day (Bates, 2007). Administering the wrong dose accounts for the most common medication errors (40.9%) that result in patient death (Hughes, 2008).

Because accurate medication calculation is vital for high-quality health care and patient safety, we designed a medication and calculation digital simulation for safe math learning: simulated Medication Mathematics (siMMath). With siMMath, we attempted to empower the development of proportional reasoning, developing this "number sense" in a design based on situated-learning theories (Brown, Collins & Duguid, 1989; Lave, 1988; Lave & Wenger, 1991). As students manipulate "tools of the trade"—digitally presented nursing objects such as syringes, ampoules, tablets, and intravenous (IV) pumps—to calculate and prepare medication for patients, they experiment with—and construct—concepts related to proportional reasoning.

The siMMath environment is part of a larger architecture aimed at addressing the gap between theory and practice in the academic teaching of practical professions, where conceptual, symbolic, and experiential understanding of learning components are engaged separately. In this paper, we focus on a symbolic space.

This paper describes how learning with the siMMath environment can support the learning of proportional reasoning. Here, we review the conceptual field of proportional reasoning through the nurse's calculation of medication dosages by focusing on the situated-learning perspective.

Proportional Reasoning

Proportional reasoning is the ability to reason about rational numbers and to compare their ratios (Noelting, 1980a, b). Based on the cognitive development approach, Inhelder and Piaget (1958) were the first to show that the proportional scheme develops in three stages: the intuitive stage, the concrete stage, and the operational formal stage. According to their theory, proportional reasoning matures from qualitative additive reasoning to multiplicative reasoning, considered to be full proportional reasoning and achieved at adolescence, about age 11. However, since Piaget's early research into the topic, many studies showed that proportional reasoning is not fully resolved at adolescence but continues to be problematic for adults (see, e.g. Courtney-Clarke & Wessels, 2014; Harries & Botha, 2013; Sowder et al., 1998). Lamon (2007) made the startling claim that "more than 90% of adults do not reason proportionally" (p. 637).

Citing Inhelder and Piaget's research, which focused on physics-based concepts, Schwartz (1988) and Kaput and West (1994) recommended that proportional reasoning be seen as a unified mathematics of quantity, which links numbers to their referents. Central to their analysis is the distinction between extensive and intensive quantities. Extensive quantities are composed of one unit of measure and can be directly counted or measured (e.g. length, time, mass, volume). Two extensive quantities can be used to construct an intensive quantity such as the concentration of a solution (Noss, Hoyles & Pozzi, 2002). The intensive quantity—for example, concentration—remains constant only when its dimensions—the mass of the solute and the volume of the solution—are enlarged or reduced proportionally. Therefore, if intensive quantity is a constant of proportionality that states the relationship between the two quantities, then the solution to such a problem demands the use of multiplicative strategies. Consequently, the ability to solve intensive quantity problems parallels full proportional reasoning (Howe, Nunes & Bryant, 2010).

Medication Calculation

Medication administration involves a range of mathematical concepts related to ratio and proportion: for example, dose-strength (concentration) calculation, frequencies, converting between different units, and setting infusion rates (Hoyles, Noss & Pozzi, 2001). Findings from nursing studies in the past 30 years paint a picture of deeply flawed proportional reasoning, the main core of medication calculation skills. For instance, in 1979, Perlstein, Callison, White, Barnes, and Edwards found that pediatric nurses (n = 95) achieved a mere average of 76.6% on a paper-and-pencil test of medication-drug calculations. This finding is consistent with that of Bindler and Bayne (1991), who found that 81% (n = 110) of nurses from four medical centers in the western United States failed to calculate medication doses at a 90% passing level. With an even larger sample of nurses (n = 1185), Kapborg (1995) found mean paper-and-pencil test results of 68%, and none of the nurses correctly solved more than 90% of the questions. Studies with nursing students reported similar results: In 2006, Wright gave a 30-item test to 71 sophomore student nurses and found that only 4.2% were able to score 75% or higher, a result replicated in other studies (e.g. Bagnasco et al., 2016; Glaister, 2007; Grandell-Niemi, Hupli & Leino-Kilpi, 2005; Wright, 2007).

Learning and Teaching of Medication Calculation

Most instruction in medication calculations uses medicine calculation formulas. For example, a common formula used by nurses is "what do you want (d), over what you've got (h), times the volume (q), or in algebraic form: $d/h \times q$." Another example is an infusion rate formula calculated by taking the total volume to be infused, multiplying it by the drop factor, and dividing by the total time in minutes. This learning strategy has been implemented with only moderate success (e.g. Greenfield, Whelan & Cohn, 2006; Rice & Bell, 2005; Wright, 2004, 2007, 2008). One obvious explanation for this low success rate is that the drug calculation formula removes the numbers from their contextual clinical meaning, such as units of measurement and visual cues such as drug charts and ampoules. Moreover, the evidence suggests that nurses do not remember the correct drug calculation formulas and that few of them actually use these formulas in their regular clinical practice (Hoyles et al., 2001; Wright, 2008, 2009).

Although few studies aimed to improve students' medication calculation skills via an intervention design, the empirical evidence for its effectiveness is inconsistent: Van Lancker, Baldewijns, Verhaeghe, Robays, Buyle, Colman, and Van Hecke (2016) showed that the traditional, face-to-face lecture approach has been more efficient than e-learning courses, and McMullan, Jones, and Lea (2012) presented evidence for e-drug calculation packages as a better method than traditional approaches. Other studies lacked a comparison group (Basak, Aslan, Unver & Yildiz, 2016; Macdonald, Weeks & Moseley, 2013) or showed a very small effect size (Harris, Pittiglio, Newton & Moore, 2014). Clearly, there is a need for more research using different educational strategies; therefore, we tackled the problem of students' medication calculation errors using a situated-learning perspective and a concreteness fading perspective.

Situated Abstraction with a Concreteness Fading Perspective

Mathematics has been described by classical cognitivists as generally applicable and abstract, whereas a situated approach confronts it with practical constraints and concerns in concrete situations. Lave (1988) underlined the importance of the relationship between knowledge taught in an education setting and knowledge used in workplace settings: "It seems impossible to analyze education—in schooling, craft apprenticeship, or any other form—without considering its relations with the world for which it ostensibly prepares people" (p. xiii). Highlighting the necessity of bridging these two aspects, Noss and Hoyles (1996) introduced the term *situated abstraction.*

Situated abstraction describes how formal mathematical meanings taught in school are reconstructed in adults in particular and in concrete working situations (Hoyles et al., 2001; Noss & Hoyles, 1996). Hoyles, Noss, Kent, and Bakker (2013) explained:

> We observed nurses calculating drug dosages in hospital wards, often in life-critical situations. They had been taught general calculation methods that trainers regarded as "efficient." In practice, however, these were not used, being replaced by drug- and patient type-specific rules that derived meaning from the situation, such as the nature of the drug, the volume of the phial in which the drug was stored, while working within its constraints. (p. 6)

The importance of situated anchors for adults at their workplaces was also demonstrated by Lave (1988), who found that people performed a calculation task more accurately during their work than when calculating the same task using a paper and pencil (see also Carraher, Carraher & Schliemann, 1985). Likewise, nurses in pediatric wards used the correct strategies for calculating medication concentrations when supported by situated ward equipment as anchors but were confused when asked to respond purely in terms of mathematical discourse (Noss et al., 2002).

Given the character of situated learning, there are long-standing concerns that learning gained from one context is not portable to another situation (Anderson, Reder & Simon, 1996; Kaminski, Sloutsky & Heckler, 2008). Thus, to support the abstraction and generalization to other contexts of nurses' proportional reasoning, we integrated the concreteness fading perspective: beginning with concrete, situated materials and then gradually and explicitly fading into abstract symbols. Concreteness fading was originally recommended by Bruner (1966). He proposed that new concepts and procedures should be presented in three progressive forms: (1) an enactive form, which is a concrete model of a concept; (2) an iconic form, which is a pictorial model; and (3) a symbolic form, an abstract model. This perspective has been proved to foster knowledge that is both grounded in a meaningful, concrete context and generalized in a way that promotes transfer (Fyfe, McNeil & Borjas, 2015; Fyfe, McNeil, Son & Goldstone, 2014).

Hence, to foster nursing students' deep understanding of ratios and proportions and to improve medication calculation, we designed the siMMath environment, which enables students to learn math using simulated ward equipment by pushing syringes, diluting solutions, splicing tablets, and manipulating IV infusion sets. The implicit manipulation of those tools is gradually and explicatively bridged to symbolic quantities' relationships using a ratio-table setup (see Fig. 1). To the best of our knowledge, no such efforts have been made and reported in the research literature.

Research Aim

The purpose of this study was to evaluate the effectiveness of the siMMath environment as a teaching strategy for proportional reasoning and medication calculation skills among nursing students and to understand how the siMMath environment facilitates the learning process.

Research Questions

1. What is the impact of learning using the two mediators—situated simulation tools and a ratio-table setup via a concreteness fading perspective—on the proportional

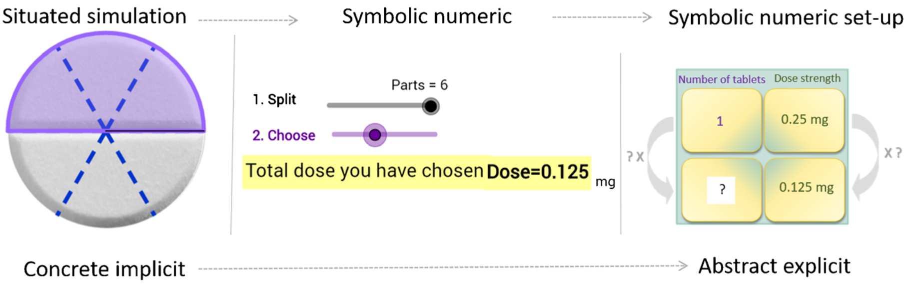

Fig. 1 A framework of materials progression used in the siMMath environment linking situated simulation tools to a ratio-table setup with a concreteness fading perspective

reasoning and medication calculation skills of nursing students compared with learning using a normal equation- and lecture-based curriculum?
2. How does learning via a concreteness fading perspective by using the two mediators—situated simulation tools and a ratio-table setup—facilitate learning of proportional reasoning, medication calculation skills, and symbolic representation patterns?

Method

The siMMath Environment

siMMath supports nursing students as they transition through concreteness fading between two mediators for concretizing medical calculations (Fig. 1). The first mediator, developed by the authors, involves situated simulation digital tools that facilitate actions relevant to preparing medication in a hospital ward. The second mediator is the ratio table, which is used as a goal representation holding the different quantities spatially in their relative proportions. The ratio-table setup was shown in previous studies to support proportional reasoning (Ercole, Frantz & Ashline, 2011).

We delivered siMMath within a learning management system by embedding simulations of dynamic and interactive digital tools designed with the open-source Geogebra mathematics software (https://www.geogebra.org/). This methodology enables students to experiment, examine, and construct their understanding of medication calculation concepts by manipulating "real" vial concentrations and cutting "real" tablets while interpreting patient records, doctor's medication orders, and drug labels (see examples in supplemental information, Appendix 1).

The first unit implemented a computerized activity (The Mathematical Imagery Trainer for Proportion) designed and researched by Abrahamson (2013) to support understanding of ratios and proportions. In this activity, the learner can reason about the proportional relationship between quantities by moving two parallel sliders to different heights to change the color of the screen, so that their proportion is a certain value, for example one-half. Through the following units, the students generalize their qualitatively expressed, manipulation-based strategies, in particular the mathematical propositions of medication calculation (supplemental information, Appendix 1).

The following units begin with a short movie clip that portrays a nurse in a hospital department explaining the calculation procedure while preparing the medicine. Each unit then moves to structured activities, where students experiment by performing "calculation actions" (e.g. cutting and collecting a group of tablets, diluting a medication in an ampoule) using digital tools (see Fig. 2). The digital tools gradually bridge to the use of a ratio table. The ratio table supports the relationship between actions on objects and quantities and is considered a structured representation for solving proportion problems: it helps organize numbers, moves students to use multiplicative strategies, and supports proportional thinking (Ercole et al., 2011). This environment incorporates a flexible instructional design using a simple-to-complex sequence of medical calculation categories. When moving between the categories, students can either use the digital tools and the ratio table or compute the amounts on their own. If students make an error, they are first offered advice that elaborates the procedure, and if this does not work, the procedure is demonstrated using a ratio table.

Research Design

The two-part study was conducted following the approval of the ethics committee at the University of Haifa's Faculty of Social Welfare and Health Sciences. Part 1 used a quasi-experimental, controlled pretest–intervention–posttest design with a quantitative analysis approach; part 2 used a case study design with a quantitative analysis approach.

Participants

Study Part 1 Participants included volunteer sophomore nursing students (***N*** = 169) in the Cheryl Spencer Department of Nursing at the University of Haifa, Israel. Students for the comparison group (***n*** = 73) were recruited 1 year before the students for the experimental group (***n*** = 96). The participants in the comparison group studied with the normative lecture-based curriculum. The reasons for the separation of the groups were threefold: to enlarge our sample, to reduce diffusion between the intervention and comparison groups as much as possible, and to prevent any resentful demoralization of comparison group students. There were no statistically significant differences in demographic characteristics and baseline academic achievements at admission between the experimental and the comparison groups (see Table 1).

The experimental study group initially included 104 students. Of these, 96 (92%) completed both the pre- and posttest questionnaires. No significant difference in pretest scores was found between students who did not complete the posttest questionnaire and those who completed both the pre- and the posttest evaluations ($t = -.83$, $p = .45$). Of the initial 89 students in the comparison group, 73 (82%) completed both evaluations. Similarly, no significant difference in pretest scores was found between students who

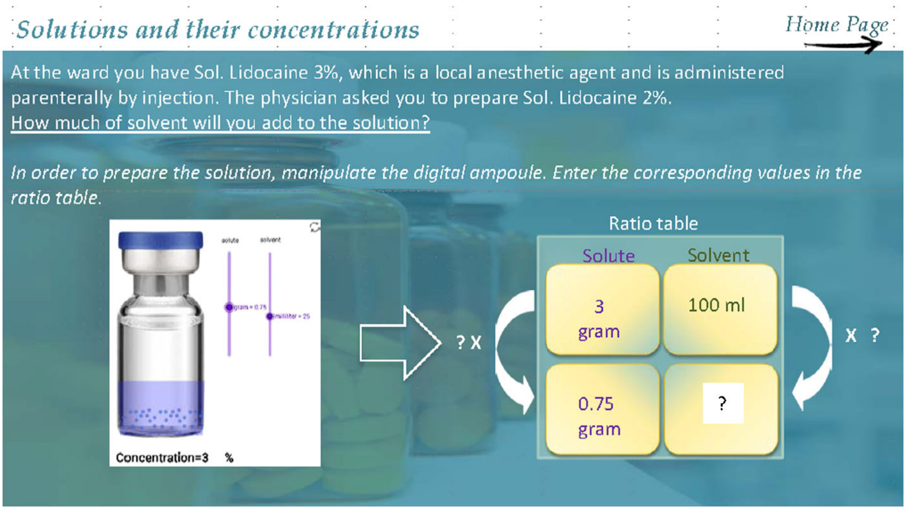

Fig. 2 Screenshot from the siMMath environment. Here, the student is asked to prepare for medical intervention a Sol. Lidocaine 2%. The student manipulates the digital ampoule, which by action on the digital tool helps the student explore the concept of concentration. The student can also set up the quantities within the ratio table to make the calculation (see link: https://ggbm.at/Gk7jKQYA)

did not complete the posttest and those who completed both evaluations ($t = -.44$, $p = .65$).

Study Part 2 For the focus group, we randomly selected seven students from the experimental group. Six were female and one was male; the mean age was 23 ± 2.8 years.

Procedure

Study Part 1 Students in the comparison group learned and practiced drug-dosage calculation with normal equation-based lecture lessons (about 180 min total). Students in the experimental group studied drug-dosage calculation with the siMMath environment (120–180 min total).

Table 1 Demographic characteristics and university entrance and course achievements: comparisons between the experimental and comparison student groups ($N = 169$)

	All students $N = 169$	Experimental group $n = 96$	Comparison group $n = 73$	Statistics[a]
	Demographic characteristics			
Age (mean ± SD, years)	22 ± 2.5	23 ± 2.8	22 ± 2.1	− 0.98 ($p = .36$)
Gender, *n* (%)				
Female	121 (71)	69 (71)	52 (70)	0.2 ($p = .65$)
Male	48 (29)	27 (29)	21 (30)	
Ethnicity, *n* (%)				
Arabs				
Muslim	71 (42)	37 (38)	34 (47)	1.6 ($p = .80$)
Christian	36 (21)	22 (23)	14 (20)	
Druze	10 (6)	5 (6)	5 (7)	
Jewish	50 (29)	31 (32)	19 (25)	
Other	2 (2)	1 (1)	1 (1)	
University entrance and course achievements (mean ± SD)				
Psychometric Entrance Test score[b]	601 ± 45	604 ± 48	596 ± 40	− 1.14 ($p = .20$)
Hebrew (YAEL test) score[c]	114 ± 11	115 ± 12	114 ± 9	− 0.46 ($p = .61$)
Chemistry course score	75 ± 37	70 ± 16	75 ± 37	1.8 ($p = .07$)
Microbiology course score	87 ± 9	88 ± 9	86 ± 9	− 0.9 ($p = .32$)
Cell-biology course score	90 ± 9	91 ± 8	90 ± 9	− 0.6 ($p = .57$)
Biology course score	90 ± 99	90 ± 8	90 ± 10	− 0.07 ($p = .94$)

[a] Based on chi-square test or independent sample *t* test where appropriate

[b] Psychometric Entrance Test is a standardized test in Israel, generally taken as a higher education admission exam. It covers three areas: mathematics, verbal reasoning, and English language

[c] The YAEL test is a Hebrew-proficiency test. Students who take the Psychometric Entrance Test in any language other than Hebrew are required to also take the YAEL test. Here, we report the mean scores of 27 students in the comparison group and 50 in the experimental group who took the YAEL test

All students completed identical pre- and post-questionnaires 2 months before and 1 month after learning medication calculation (on the last day of the academic semester).

Study Part 2 To observe firsthand the process of learning with the siMMath environment, we recorded the screens of seven randomly selected students from the experimental group as they worked in the siMMath environment. This information was captured with Camtasia (https://www.Techsmith.Com/Camtasia.Html).

Data Collection Instruments

Study Part 1. Medication Calculation Questionnaire (MedC) The MedC questionnaire was developed for this study to assess nursing students' medication calculation competency. The items were validated by experienced lecturers in the nursing department, to ensure alignment with both content and difficulty level. The MedC includes 12 multiple-choice questions comprising four main categories of medication calculation: (1) solid medications (1 item), (2) unit conversion (3 items), (3) concentration (3 items), and (4) infusion rate (5 items). The four main categories were based on previous medication calculation subscales developed by Coben and Weeks (2014) and McMullan et al. (2012). Analysis of the MedC questionnaire using Cronbach's alpha yielded a high internal consistency score of .78.

Noelting's Proportional Reasoning Test (Noelting's Test) To assess students' abstraction of proportional reasoning and its generalizability to contexts unrelated to medications, we used a proportional reasoning test developed by Noelting (1980a). He sorted intensive quantity problems by difficulty based on student responses to 25 mixing problems, in which students compared two ratios of various concentrations of orange juice and water (see supplemental information, Appendix 2).

Noelting (1980b) posited rules for the items characteristic of the Piagetian cognitive-stages hierarchy of proportional reasoning—the intuitive, the concrete operational, and the formal operational (Inhelder & Piaget, 1958; Piaget, 1950). Noelting performed a Guttman scalogram analysis of data based on this test and determined that the 25 items formed a linear hierarchical scale. The test has been used with children, adolescents, and adults (e.g. Bart & Williams-Morris, 1990; Draney & Wilson, 2007). In this research, we used two items from the concrete operational category, related to the additive strategy of manipulating extensive quantities, and three items from the formal operational cognitive category, related to the multiplicative strategy of manipulating intensive quantities, which are more appropriate for adult students (Howe et al., 2010).

Missing-Value Proportion-Problems Setup-Edification Guide (MVPP Setup) We adopted this guideline from Deichert (2014) to classify students' hand-written setups (symbolic representations) to solve problems on the MedC questionnaire before and after learning with the siMMath environment. Ercole et al. (2011) stated that "when solving problems involving proportions, students …intuitively draw on strategies that connect to their understanding of fraction, decimals, and percent" (p. 483). Therefore, analysis of students' setups helped the authors understand students' learning patterns and levels of proportional reasoning (Vergnaud, 1982).

Deichert (2014) proposed seven categories of possible notation setups (symbolic representations) for solving proportions: (1) equality of measures, as the construct sets of two measures equal to each other; (2) ratio table, a two-column table for tracking quantities that covary multiplicatively; (3) double number-line diagram, two parallel number lines with corresponding values; (4) analogies; an example of a general analogy is a:b:: c:d using ratio notation; (5) equal ratios, written in fractional form (a/b = c/d); (6) dimensional analysis, or multiplication by the ratio using extensive measures and unit labels; and (7) the nursing rule, for example a formula for calculating infusion rates.

Study Part 2. Screen and Video Recordings To assess the learning process of students whose activities were recorded, we measured how long it took them to complete each topic of medication calculation and counted the number of mistakes they made and how frequently they used the embedded digital tools.

Data Analysis

Study Part 1 Responses to the MedC questionnaire and to Noelting's test were coded as correct or incorrect answers, and total scores were calculated as the percentage of correct answers. The pre- and posttest results, including the overall score and the scores for each of the subscales, were analyzed using descriptive statistics (mean, SD). Gained knowledge following learning with siMMath was calculated as posttest score minus pretest score. These scores were compared using a Mann–Whitney *U* test for nonparametric data with an effect size of *r* (Fritz, Morris & Richler, 2012).

The students' setup calculations at pre- and posttest were analyzed and coded using the MVPP setup guide and compared with a chi-square test. Students' use of a ratio table as a calculation setup was related to MedC and Noelting's test scores with a Mann–Whitney *U* test for nonparametric data.

Study Part 2 Students' progress within the siMMath environment was captured with screen and video recordings of seven students and then coded according to four simple-to-complex topics related to medication calculation: solid medication, unit conversion, concentration, and infusion rate. The progression was coded for two variables: time to complete the topic (in minutes) and frequency (in percentages) of using digital tools. The measures were analyzed using descriptive statistics (mean, SD) and related using nonparametric Spearman correlations to the categories of the medication calculation complexity sequence within the siMMath environment. Data were analyzed with SPSS (version 21, IBM Corporation, Armonk, NY).

Results

Findings are presented with respect to the two research questions.

Research Question 1: the Impact of Learning with the siMMath Environment

Findings are presented for the following: MedC questionnaire scores, Noelting's test scores, and their relationship.

Medication Calculation Competency Students' medication calculation skills were assessed using the MedC questionnaire. Descriptive and inferential statistics for the MedC pre- and posttest questionnaires are presented in Table 2.

Overall, the learning gains for the experimental group were significantly higher than those for the comparison group, with a moderate to strong effect size. When broken down by subscale, results showed a significant learning gain for the more advanced and difficult concentration and infusion rate subscales. For these subscales, a ceiling effect for the experimental group in the posttest was found, as the average score was almost 100%.

Noelting's Test Students' abstraction of proportional reasoning was explored with Noelting's test. Overall learning gains for the experimental group were significantly higher than those for the comparison group, with a moderate effect size (see Table 3). When broken down by subscale, the difference between the groups was only found for the highest level of proportional reasoning, the Formal Operational subscale, where the experimental group's advantage is clearly seen.

Relationship between Medication Calculation and Noelting's Test The results for Noelting's proportional reasoning test were related to the MedC questionnaire and its subscales (Table 4). We found that two subscales—medical calculation for infusion rate and concentration—have a positive moderate correlation with the Formal Operational subscale of Noelting's test (Table 4; $r = .30$, $p < .01$). Thus, the higher the degree of formal operational proportional reasoning, the higher the scores for infusion rate and concentration calculation.

To summarize, we show that the learning gains for the experimental group were significantly higher than those for the comparison group on the MedC questionnaire and on Noelting's test for the highest level of proportional reasoning.

Research Question 2: Facilitation of Learning with the siMMath Environment

Findings are presented for the proportion-problems setup and for the screen and video analysis.

Proportion-Problems Setup Analysis of students' setups to respond to the MedC questionnaire revealed that use of a ratio-table setup was the predominant pattern before learning with siMMath (40% of students). Equal ratios (19%), dimensional analysis (19%), and the nursing rule (16%) were the next three most frequently used setups. The equality of measures (5%) and analogy (1%) setups were less common. After learning with siMMath, students shifted significantly ($\chi^2 = 68$, $p < .001$) toward using a ratio-table setup: 82% used a ratio table for a quantities setup, 6% used equal ratios, 5% used the nursing rule, 3% used dimensional analysis, 3% used equality of measures, and 1% used an analogy.

Table 2 Medical calculation (MedC) questionnaire descriptive and inferential statistics ($N = 169$)

	Pretest score (%)		Posttest score (%)		Learning gain (%)[a]		Statistical tests	
	Exp. ($n = 96$)	Comparison ($n = 73$)	Exp. ($n = 96$)	Comparison ($n = 73$)	Exp. ($n = 96$)	Comparison ($n = 73$)	Mann–Whitney U	Effect size, r
Medical calculation overall	66 ± 23	66 ± 29	94 ± 7	78 ± 16	28 ± 24	12 ± 29	2217***	0.30
Subscales (increasing complexity)								
Solid medication	90 ± 29	74 ± 44	88 ± 32	86 ± 34	− 2 ± 43[b]	12 ± 53	2925	0.15
Unit conversation	54 ± 33	63 ± 39	86 ± 21	84 ± 23	32 ± 39	21 ± 40	2886	0.13
Concentration	56 ± 33	66 ± 39	97 ± 9	79 ± 23	41 ± 33	13 ± 41	1890***	0.36
Infusion rate	72 ± 30	66 ± 38	97 ± 6	67 ± 29	25 ± 29	0 ± 39	2014.5***	0.34

Data are represented as mean ± standard deviation, range 0–100

Exp. experimental group

***$p < .001$

[a] Learning gain was computed to compensate for differences in prior knowledge of MedC questionnaire: (postscore − prescore)

[b] The difference between pre- and posttest scores in the comparison group is not significant, paired t test, $p > .05$

Table 3 Noelting's test descriptive and inferential statistics ($N = 169$)

	Pretest score (%)		Posttest score (%)		Learning gain (%)[a]		Statistical tests	
	Exp. ($n = 96$)	Comparison ($n = 73$)	Exp. ($n = 96$)	Comparison ($n = 73$)	Exp. ($n = 96$)	Comparison ($n = 73$)	Mann–Whitney U	Effect size, r
Overall	82 ± 24	81 ± 25	93 ± 15	77 ± 26	11 ± 22	− 4 ± 28[b]	2372***	0.31
Sub-scales								
Concrete operational	95 ± 15	89 ± 23	98 ± 8	87 ± 23	3 ± 18	− 2 ± 28[b]	3195.5	0.11
Formal operational	73 ± 36	75 ± 34	90 ± 24	69 ± 38	17 ± 36	− 5 ± 40[b]	2454***	0.30

Data are represented as mean ± standard deviation, range 0–100

***$p < .001$

[a] Learning gain was computed to compensate for differences in prior knowledge of Noelting's test: (postscore − prescore)

[b] The difference between pre- and posttest scores in the comparison group is not significant, paired t test, $p > .05$

At posttest, no significant difference for student's calculation setups and MedC questionnaire scores was revealed ($U = 377$, $p = .53$). Relating students' calculation setups at posttest to Noelting's test scores with a Mann–Whitney U test revealed that formal operational scores were higher for the ratio-table setup (99% ± 0.06%, median = 100%) than for the other setups (91% ± 19%, median = 100%), ($U = 356$, $p > .01$).

Screen and Video Recordings To further evaluate the learning processes, we analyzed the screen and video recordings of seven students as they learned with the siMMath environment. This analysis made clear when and why students used the optional digital

Table 4 Correlations (Pearson r correlation) between learning gains on Noelting's proportional reasoning test and medical calculation scores within experimental group ($n = 96$)

	Overall: Noelting's test	Subscale: concrete operational	Subscale: formal operational
Medical calculation (MedC) overall	0.31**	0.07	0.30**
MedC subscales (increasing complexity):			
Solid medication	0.01	0.08	− 0.006
Unit conversation	0.09	0.01	0.09
Concentration	0.29***	0.15	0.28**
Infusion rate	0.30**	0.01	0.31**

**$p < .01$, ***$p < .001$

math simulations. The two variables used to characterize a student's tendency to use digital simulations (time to complete and frequency of using the simulation) were related to the four math calculation categories (from simple to more complex) of the siMMath environment: solid medication, unit conversion, concentration, and infusion rate. A significant Spearman's correlation was found between the *complexity level of the medication calculation* and the *frequency of using the embedded simulations* (r_s = .82, $p < .001$) and the *time* students spent on each topic (r_s = .86, $p < .001$). Students tended to use the digital simulations more often and to spend more time completing the challenges (Fig. 3) when learning the more complex categories of medication calculation.

To conclude, we found that the complexity level of the medication calculation categories within the siMMath environment influenced learning process time and tendency to use digital simulations. Furthermore, students' shift toward using a ratio table as a setup at posttest may have influenced their proportional reasoning. We elaborate on these findings in the "Discussion" section.

Discussion

In this study, we anchored learning of proportional reasoning in the use of situated simulation professional tools with a concreteness fading perspective. Because proportional reasoning is the basis for medication calculation, we enabled students to construct their proportional concepts within the siMMath environment by manipulating, experimenting, and calculating with situated "tools of the trade"—syringes, ampoules,

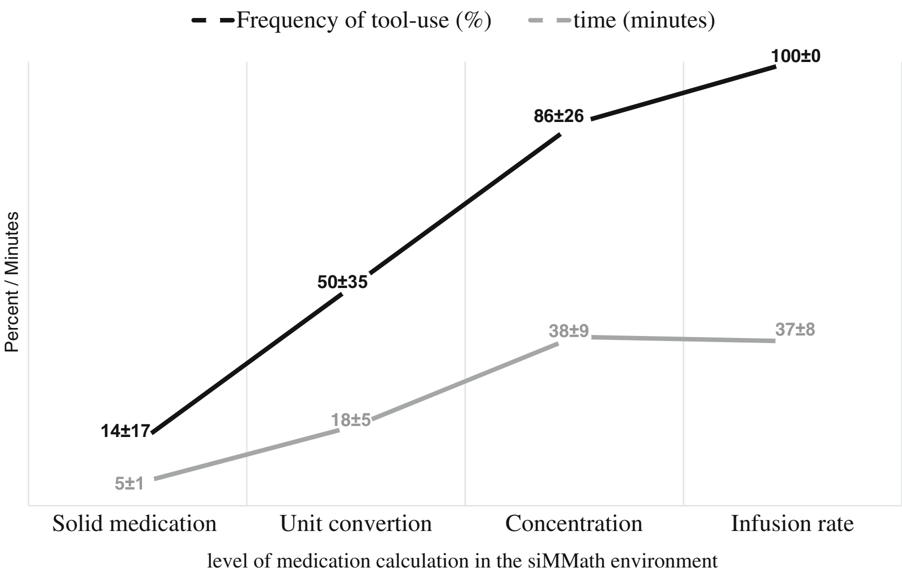

Fig. 3 Relationship between complexity level of medication calculation in the siMMath environment and frequencies (%) of use of situated simulation tools and time to complete each topic (n = 7). Data are presented as mean ± standard deviation

tablets, and IV pumps. This implicit manipulation of simulated tools was gradually and explicatively bridged to a symbolic quantities relationship with a ratio-table setup.

To evaluate students' medication calculation competency, we used four main categories of medication calculation problems (MedC questionnaire). We found that the main significant difference between nursing students who learned with the siMMath environment and those who learned with the normal equation- and lecture-based curriculum involved the more challenging categories of medical calculation problems: concentration and infusion rate. These findings can be explained through a distinction between extensive and intensive quantities as it relates to the full proportional reasoning level (Howe et al., 2010; Inhelder & Piaget, 1958). The difference between the levels of proportional reasoning is connected to the way the quantities are treated: manipulations of solid medications through weight or unit conversions can be considered extensive quantities because they are composed of one unit of measure; manipulations of concentration and infusion rate measures can be considered intensive quantities because of the proportional relationship between the quantities—concentration is a relationship between mass and volume, and infusion rate is a relationship between volume and time. Intensive quantities require formal operations, which are characterized by multiplicative thinking, and are thus challenging (Howe et al., 2010, 2011). Hence, it would seem that learning with siMMath helped nursing students shift their understanding and practice both with situated calculations and at a higher level of medication calculation.

These findings are consistent with situated-learning theory, which has spawned a series of key mathematics and numeracy studies and characterized problem-solving strategies in everyday situations and on-the-job training (Carraher, 1986; Carraher et al., 1985; Hoyles, Noss, Kent & Bakker, 2010; Lave, 1977; Price-Williams, Gordon & Ramirez, 1969; Reed & Lave, 1981; Saxe, 1988). As students learned within the siMMath environment, their implicit calculations using situated simulation math tools gradually faded into the use of symbolic and abstract quantities. We may assume that these students exhibited, via Noelting's test, a better abstraction and generalizability of proportional reasoning to situations unrelated to medication calculation, specifically reaching the formal operations level. We also found a significant correlation between medication calculation gains and abstract formal operational reasoning. These findings emphasize the advantage of linking situated learning with the concreteness fading perspective: anchoring learning in situated digital tools and then successively fading it to abstract numerical symbols (Fyfe et al., 2014, 2015; Noss & Hoyles, 1996). Situated learning can be transferred when abstract symbolic quantities become explicitly visible and connected while one is performing implicit calculation actions on situated tools, such as cutting pills.

The siMMath environment facilitated learning through a ratio table as a predominant calculation setup. Students who used this setup for calculation had higher formal operational scores on Noelting's test. In accordance with this finding, "the ratio table is a flexible computational tool that both acts as a visual pattern to aid in operating with rational numbers and connects different notations of rational numbers" (Middleton & van den Heuvel-Panhuizen, 1995, p. 284). A benefit of the ratio table is its flexibility to encourage different relational calculi (Gravemeijer & van Galen, 2003). Ercole et al. (2011) showed that the ratio table could help students transition into setups requiring the use of a scalar or function relationship rather than scalar decomposition, namely that it supports proportional reasoning. Moreover, a ratio table aligns the situated and abstract aspects of calculation by holding the quantities in a constant spatial relationship. Recent studies have repeatedly demonstrated that physical spacing plays an important role in arithmetic computation (Kirshner & Awtry, 2004; Landy & Goldstone, 2007, 2010). Arithmetic operations are easier to learn when they conform to certain spacing practices. Hence, the ratio-table representation may enhance generalization to other contexts by holding the different quantities spatially in their relative proportions.

In this study, we were able to understand the role of each of the two mediators, namely the ratio setup table and the digital situated tools, by analyzing the processes of learning. The importance of the ratio table as a mediator showed in students' significant shift toward using a ratio-table setup after learning with the siMMath environment and its relation to higher scores on Noelting's test. The centrality of the digital situated simulations as mediators for medication calculation understanding can be also illuminated by our case-study results. The findings suggest that a student's tendency to use the embedded digital math simulations was influenced by the complexity of the medication calculation involved. When a medication calculation assignment was related to concrete operational proportional schemes, students did not need the mediations of digital simulations. But when a calculation required more complex operations, students used digital simulations that were grounded in previous experience and that enabled them to construct their own understanding and then, using a ratio-table strategy, apply it to symbolic math. It follows that more complex math operations require use of the mediators, concretizing with simulated tools and successively fading into a ratio-table setup, especially for calculating intensive quantities. Thus, rich situated concretizing can mediate and enhance abstract formal proportional reasoning.

Limitations

Our study has several limitations. Due to our need to prevent diffusion of the treatment between the comparison and the experimental groups, randomization did not apply. Another limitation of our research was the dropout rate just before completing the posttest questionnaires in both the comparison and the experimental groups. Because participation was voluntary during a highly stressful semester, the students struggled to find time to complete the questionnaires.

To evaluate the advantages of learning with siMMath, further work should be performed on a large scale, with different types of healthcare providers (e.g. registered nurses), comparing it not just with lecture-based education but with other simulation approaches and tools, for example with e-drug calculation packages (McMullan et al., 2012). In addition, in this research we evaluated the mutual influence of two mediators; further research should evaluate the contribution of each mediator to the learning process separately.

Conclusion

Our main findings revealed that learning with siMMath is highly efficient in promoting an understanding of intensive quantities—concentrations and infusion rates—which demands formal operations, a multiplicative form of thinking. Moreover, we showed that the concreteness fading perspective between the two mediators (situated simulation tools and a ratio-table setup) enhances abstract proportional reasoning.

We also showed that the siMMath environment can prepare students for safe drug-administration practice, which eventually can reduce drug calculation errors in hospital wards. We suggest that our findings offer a specific model for more accurate medication calculation among nursing students, and a more general model for other safety-critical vocational and mathematic on-the-job contexts.

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