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## Promoting adaptive number knowledge through deliberate practice in the Number Navigation Game

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**Abstract.** Strengthening adaptive expertise in mathematics education through deliberate practice is a challenging task in traditional classrooms. The purpose of this study was to investigate whether Number Navigation Game (NNG) promotes deliberate practice and how the game performance profiles relate to Adaptive Number Knowledge (ANK) development, perceived challenge, flow, and math interest. NNG is a game-based learning environment that requires students to progress by making more complex arithmetic solutions, which is particularly important to promote ANK. Game performances of 214 Finnish students require not only addition and subtraction but also multiplication and division operations were compiled and compared to the best performance possible for each level. A growth mixture model based on students' relative performance levels was employed to offer insight into the changes in students' game performance throughout the game, and the relations of students' game performance with knowledge gains, perceived challenge, math motivation, and flow. We identified four profiles of students' game performance. The largest profile steadily enhanced their performance in playing the game despite having lower-than-average initial performance. This group experienced lower flow and larger learning gains than other groups, which suggests their engagement may be more aligned with deliberate practice.

**Keywords:** Adaptive number knowledge, Gaming analytics, Game-based learning, Deliberate practice, Mathematics.

### 1 Introduction

Adaptive expertise is a highly valued outcome of mathematics curricula [1] and is expected to typify exceptional mathematical thinking (e.g. [2]). Adaptive expertise reflects knowledge that can be flexibly applied in novel situations, not just within highly constrained or well-rehearsed contexts. Adaptive number knowledge (ANK) is a quality of adaptive expertise in arithmetic, which reflects a well-connected network of knowledge of numerical characteristics and arithmetic relations[3]. ANK was found to differentiate even among students with high levels of math achievement and predicted later algebraic knowledge [4]. To develop ANK, it is crucial that students are provided with opportunities to practice solving open-ended mathematical problems in novel

circumstances. However, it is usually difficult to achieve such conditions in the larger context of a traditional classroom for all students.

In fact, practice in math classrooms is often connected to the automatization of procedural skills [5] and static routine expertise development [6]. There are a lack of pedagogical models for supporting the development of adaptive expertise in school mathematics [5]. For example, mechanical practice with procedures of rational number arithmetic alone does not lead to long-term and sustainable learning results [7]. In other words, not all practice is equally beneficial. With the affordances of game-based learning, it is possible to overcome these limitations. Game mechanics can align with deliberate practice's principles while offering an open-ended learning environment that would trigger reflection on different solutions to arithmetic problems [5] and possibly lead to improvements in ANK [4].

### **1.1 Deliberate practice in math education**

There is a need for more complex forms of practice in mathematics classrooms, especially deliberate practice (DP) [5]. DP has proven to be the key factor in explaining extraordinary development in different domains [8]. In the realm of mathematics education, it is especially important to provide students with opportunities to engage in more complex forms of practice that push them to develop their emerging skills and knowledge structures (i.e. DP) rather than just routine and static practice with their existing skills (drill-and practice) [5].

Due to conventional educational setting constrains and demanding conditions of DP's principles, it is difficult to systematically implement DP approach in authentic math classrooms. However, previous research suggests that it is possible to apply some core aspects of DP in well-designed game-based learning environments. In the Number Navigation Game, design principles align with some core principles of DP. For example, players are provided with tasks that are (a) ideally challenging and well-suited for individual students, (b) offering opportunities to practice at the edge of their competence, (c) providing them with continuous feedback to improve their current skills, and (d) the tasks are situated in open-ended learning environment that can trigger reflection on different solutions to arithmetic problems [9]. Previous studies on NNG resulted in students' strong adaptive number knowledge development, and transferable pre-algebra skills [4],[10].

Research on gaming has emphasized the importance of flow as desirable experience during the game play. Both flow and deliberate practice refer to strong involvement in a situation. However, there are fundamental differences between these phenomena. When developing the flow concept, Csikszentmihalyi [11] analyzed the nature of the process when high level experts (e.g. chess players and rock climbers) pursued enjoyable activities on optimal level of challenge. However, Ericson et al. [12] showed that the deliberate practice enhancing expertise is a conscious, and sometimes unpleasant, practice when people tried to go beyond their current skill level. Thus, we can assume that in a mathematics serious game, deliberate practice may be related to persistent but slow process, low flow experience and high feeling of challenge.

## 1.2 Promoting adaptive number knowledge with game-based learning

Promoting students' ANK is challenging and often demands a great quantity of variable practice [4]. This practice has to be complex, with varying numbers and operations, while offer multiple strategies for solving arithmetic problems, and opportunities for students to contemplate on their solutions and underlying relations [13]. Teaching in many classrooms usually involves teaching various problem solving strategies, which does not lead to strong ANK in most students [14]. Ideal training environments need to incorporate numerous attempts to strengthen students' underlying knowledge of numerical relations while offer a large amount of practice with open-ended arithmetic problems [5]. With technological improvement, game-based learning offers many opportunities to develop complex and flexible mathematical learning environments that would meet the needs of such demanding learning environments. The NNG aims at improving primary school students' ANK by providing different opportunities to engage in strategic work with various combinations and operations with the use of the 100-square as the external representation of whole numbers (1-100) [15]. However, it is unclear exactly if and how students engaged in deliberate practice while playing the game, nor how that influenced their learning outcomes and perception of the game.

## 1.3 Present study

Previously, NNG was found to be effective in promoting ANK, with a basic measure of game performance (number of levels completed) predicting learning gains [15]. The design of NNG has been argued to support DP [9]. However, there is not any direct evidence suggesting that students engaging with DP while playing the game.

In this study, we aim at better understand different ways that students engaging in playing NNG, and to determine whether there can be found evidence on deliberate practice in the gaming analytics and learning outcomes. Thus, we ask:

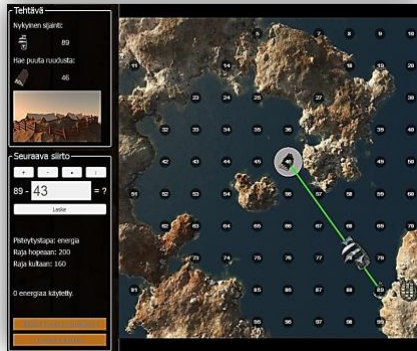
- (1) What are the different profiles of game performance?
- (2) How are the profiles of game performance related to mathematics learning outcomes, experienced flow and challenge during gameplay, and math interest?

## 2 Method

### 2.1 Participants

Participants were 214 fourth to sixth grade students ( $M$  age= 11.37,  $SD$ = 7.13) selected from a larger sample of 642 student who took part in a large-scale RCT over a ten-week period [15]. Participants in the present study were those who finished at least 5 Energy maps (see 2.2. for description). Participation was voluntary, and informed consent forms were gathered from the participants' parents. Ethical guidelines of the University of Turku were followed strictly.

## 2.2 Description of the Number Navigation Game



**Fig.1.** Example of a map in the Energy scoring mode in NNG 1.

NNG has an “intricately integrated” design [16] in which the gaming mechanism is integrated directly to the mathematical content. Gaming interface is 100 squares superimposed on different maps of land and sea, where players’ task is to collect four different raw materials to build settlements. To progress, players need to navigate a ship from a starting number (the harbor) to retrieve a material on a given point and return to the harbor by applying various combinations of numbers and arithmetic operations. For instance, in Fig. 1, the player starts from number 89 and has to collect wood situated at number 46. The player needs to input mathematical equations on the left side of the screen. The moves have to take the ship to the targeted material (number 46) while avoid numbers that covered by land. The map is completed when all four of the materials are retrieved. In this study, students’ game performance and analytics were collected within the frame of the large-scale RCT in spring 2014 where students played the first complete version – NNG 1. The game has two scoring modes: Moves and Energy scoring. In the Moves mode, players need to retrieve the materials and return to the harbor using the least number of moves (operations). In the Energy scoring mode, the idea is to use the least amount of “energy”, which is measured by adding up all the numbers inputted in the operation box. The Moves mode aims to trigger the use of addition and subtraction with larger two-digit numbers, while the Energy mode requires more complex arithmetic relations and players need to use all four arithmetic operations. Hence, the Energy levels are considered to be particularly important for promoting ANK. For more information about the developmental process of NNG and roles of game features in enhancing adaptive number knowledge see [16, 17]

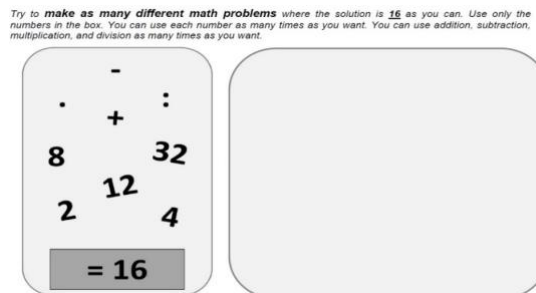
## 2.3 Measures

Prior to and after the intervention students completed measures of ANK, arithmetic procedural fluency (Woodcock-Johnson Math Fluency sub-test), pre-algebra

knowledge (missing-value problems, e.g.  $12 + \_\_\_ = 11 + 15$ ) and math interest. Post-test also included questionnaire measuring core dimensions of gaming experience including perceived Challenge and Flow.

*Game performance* was measured with a Relative energy score (map neutral measure of performance = Score/ Gold Standard) from at least 5 completed Energy maps (T1-T2 is first two maps completed, T3 is the average of mid-maps, T4-T5 is the last two completed maps). Players complete a map by retrieving all four materials, depending on how optimal their arithmetic solutions are, their performances (or scores) will earn them either Copper, Silver or Gold coins, in which Gold coins solutions are considered close-to-optimal solutions.

*Adaptive Number Knowledge* was measured with the Arithmetic Sentence Production Task [4]. The task is a timed, paper-and-pencil instrument which measures students' ability to recognize and use different numerical characteristics and relations during their problem solving. An item includes four to five given numbers (e.g. 2, 4, 8, 12, 32) and the four basic arithmetic operations, and the aim is for students to produce as many arithmetic sentences that equal the target number (e.g. 16) as they can in 90 seconds. Total number of items are 4 and Cronbach's  $\alpha$  reliability value for the total number of correct solutions across the four items was .70



**Fig. 2.** Example of an Arithmetic Production Task.

*Arithmetic Procedural Fluency* was measured by the Woodcock-Johnson Math Fluency sub-test [18] which includes a total of 160 items. Students were asked to complete as many arithmetic problems as possible in 3 minutes.

*Perceived Challenge and Flow* were measured as part of the Gaming Experience Questionnaire which aim at capturing eight core dimensions of game experience. The questionnaire was translated in Finnish [19] and simplified in language and in length to be more suitable for the age of participants (see [20]).

*Math Interest* was measured as part of the Expectancy Value Math Motivation questionnaire (see [20]) with three items (e.g. “ I like Math”).

## 2.4 Procedure

In order to capture patterns of performance across the Energy maps, a series of growth mixture models were estimated using Mplus version 8.4. Growth mixture models are a

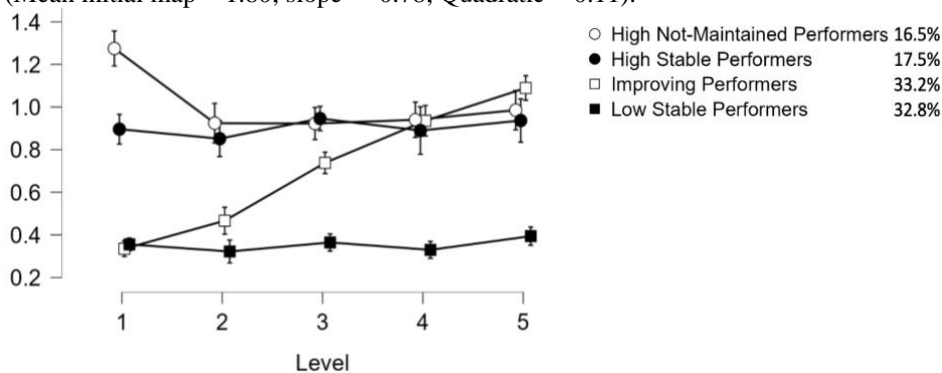
clustering procedure that identifies coherent profiles based on individuals' estimated growth curves. Individuals' initial scores of Energy map performance and their linear and quadratic slopes were estimated and used as indicators in for defining a categorical variable of profile membership (e.g., a cluster membership). We set the number of profiles in the model starting with one profile and increasing the number of profiles. Each subsequent model is compared using a set of statistical indicators [21] and theoretical considerations [14]. Once the most appropriate number of profiles is determined, we used a 3-step approach [22] to examine the relation between profile membership and external variables (i.e. ANK, math interest, etc.).

### 3 Results

#### 3.1 Profiles of game performance

The four-profile growth mixture model was most appropriate based on its lowest BIC value of the two to seven profile models [21], in addition to the fact that the 5-profile model introduced an extremely small profile (1% of sample), that did not appear theoretically founded. Figure 3 displays the mean scores and standard errors for each profile across the five game maps.

The *Low Stable Performers* profile (68 students) had lower than average performance on all energy maps (Mean initial map = -0.64; Slope = -.12; quadratic = 0.01). The *Improving Performers* (72 students) profile had lower than average initial performance but improved their performance on every Energy map (Mean initial map = -0.69; Slope = 0.51; Quadratic = -0.04). The *High Stable Performers* profile (38 students) had higher than average and stable performance on all energy maps (Mean initial map = 0.81; slope = -0.01; quadratic = -0.03). The *High Not-Maintained Performers* profile (35 students) had initially very strong performance, with an immediate drop to stable above average; it was the only profile with a non-linear slope (Mean initial map = 1.80; slope = -0.78; Quadratic = 0.11).



**Fig. 3.** Mean scores of relative game performance scores by growth mixture model profile for each game map. Error bars represent 95% confidence intervals.

**Table 1.** Means, standard deviation (in parentheses) of pre and post-test of adaptive number knowledge (ANK) and Woodcock-Johnson arithmetic fluency (AF), pre-test math interest and post-test of gaming experience.

	<b>Low Stable Performers</b>	<b>Improving Performers</b>	<b>High Stable Performers</b>	<b>High Not-Maintained Performers</b>
Pretest ANK	3.34 (1.31)	4.24 (1.84)	4.0 (1.47)	4.44 (1.69)
Posttest ANK	3.89 (1.68)	5.2 (2.07)	4.9 (1.44)	5.52 (2.36)
Pretest Arith Flu	68.81 (17.0)	77.22 (17.04)	80.66 (16.56)	77.76 (14.7)
Posttest Arith Flu	79.74 (15.67)	89.53 (18.32)	88.72 (16.91)	88.29 (19.61)
Math interest	2.90 (1.0)	3.4 (0.87)	3.46 (0.96)	3.3 (0.99)
Flow	2.06 (0.93)	1.94 (0.7)	2.41 (0.98)	2.17 (0.9)
Perceived challenge	2.43 (0.7)	2.35 (0.66)	2.72 (0.80)	2.45 (0.68)

Using the 3-step approach, we tested if the profiles differed in their prior knowledge of ANK and math interest. The *Low Stable Performers* profile had lower pretest ANK than the *High Not-Maintained Performers* (beta = .51; SE = .16;  $p = .001$ ) *High Stable Performers* (beta = .35; SE = .15;  $p = .02$ ) and *Improving Performers* (beta = .46; SE = .14;  $p = .001$ ) profiles. *Low Stable Performers* profile had lower math interest than the *High Stable Performers* (beta = .68; SE = .27;  $p = .01$ ) and *Improving Performers* (beta = .68; SE = .24;  $p = .004$ ) profiles.

### 3.2 Game performance, learning outcomes & game experience

Using a 3-step approach, we tested if the groups differed in their posttest ANK scores after controlling for their pretest scores. Tests of multinomial logistic regressions revealed that *Improving Performers* had larger gains in ANK than the *Low Stable Performers* profile (beta = -0.48, SE = 0.22; Odds ratio = 1.58;  $p = .03$ ). The *Low Stable Performers* also had lower posttest ANK (after controlling for pretest) than the *High Stable Performers* and *High Not-Maintained Performers* profiles (beta >.48; SE = .22;  $p < .03$ ). There were no other differences in learning between the other profiles.

In order to test the specificity of the effects of gameplay on ANK, we also examined if there were differences in learning gains for arithmetic fluency between the profiles. Using the 3-step approach, we found no differences between the profiles in posttest arithmetic fluency, after controlling for pretest scores.

There were only minor differences between the groups in Flow experience. *High Stable Performers* profile had higher self-reported Flow than the *Improving Performers* profile (beta = .63; SE = .25;  $p = .01$ ). There were no other differences in Flow experience. Likewise, the *High Stable Performers* profile had higher levels of perceived Challenge than the *Improving Performers* profile (beta = .81; SE = .38;  $p = .03$ ).

#### 4 Discussion and conclusions

Our results suggest that NNG does provide some students opportunities to engage in DP in support of their ANK. We found that among the four profiles of game performance, *Improving Performers* steadily enhanced their game performances in every Energy map despite lower-than-average initial performance. They had strong learning gains in ANK, and they reported a lower flow experience. We argue this is clear evidence that this group of students engaged in DP during the gameplay. As previously discussed, those who take part in DP in the NNG might undergo a low flow experience, a slow yet persistent process as they advance in the game. One of the characteristic features of DP is that it requires trying things that are just beyond a person's current abilities. It also demands a person's full concentration and attention [12]. Another reason for us to believe this group had "deliberately practiced" the Energy maps is due to the design of this NNG version. As this was the first complete working version, usability and clarity of game interface were not yet optimal. Previous study confirmed that students' gaming experience in NNG 2 significantly improved compared to those in NNG 1[16]. Hence, those were able to improve their game performance despite these usability shortcomings, especially in the more complex maps as in the Energy mode, they would have to consciously make the decision to play the game more times than needed. In other words, they deliberately chose to practice and look for different alternatives to find the more efficient solutions. This kind of practice is possible because the flexible and open nature of the game is supported with fixed and clear rules (i.e., game modes, materials retrieving to and from harbor, etc.) and novel contexts (i.e., map layouts, positions of harbor, ship, and materials, etc.), which allow students to practice and improve their game performances.

Regarding the challenge dimension, there were not big differences between the groups, except that, contrary to our expectation, *High Stable Performers* had higher level of perceived challenge than *Improving Performer*. This difference can be due to the retrospective measure, as *Improving Performer* had continuously improved their performance, therefore at the end their perceived challenge was lower. Results from pre-tests of prior mathematical knowledge and math interest shows that *Low Stable Performers* had lower-than-average in all prior knowledge (ANK and AF) and math interest. Although their game performance remained stable at lower-than-average position consistently, this group still gained significant improvement in their ANK and AF. However, their gains are expectedly smaller than other profiles (after controlling for pretest). The results are in accordance with previous studies [20] that NNG seems to be more motivating and beneficial to those who already have higher math interest.

There are several limitations in our study. Firstly, while using game logs to determine the four-profile memberships allows us to identify different profiles of game performance and their development trajectories, we know little about other external

factors such as classroom conditions or teachers' support. Also, future studies should include other types of game analytics to measure students "in-game experience" [23] and explore the roles of teachers with NNG in the classrooms. Next, we argued that one group engaged in DP based on their game performance, learning gains, lower flow experience and game design. However, we are uninformed about their patterns of practice, or why the game only enabled DP for one group. How to trigger DP and maintain such vigorous activity in game-based learning environments to as many students as possible are questions that remained unexplored. Also, prior knowledge of the *Low Stable* group is lower than *Improving Performers*, therefore it might limit their capacities in self-initiating more intense practice. Thus, more attention is needed in future studies on students' prior knowledge. Lastly, it is also worth examining whether the NNG trigger DP behaviors in *Low Stable*'s game performance in easier game levels (for instance when the game requires only addition and subtraction operations).

Despite these limitations, this study answers unaddressed question about the relations between game performance and learning development; it sheds light on the little-known application of deliberate practice in mathematics education via game-based learning platforms. The results indicated that while both adaptive expertise in mathematics and deliberate practice are very demanding and challenging concepts to directly apply in authentic settings, well-designed game-based learning environments offer unprecedented opportunities to overcome those limitations and provide unmatched advantages to "cultivate mathematical minds" in the future [5].

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