Scalebridge: Design and Evaluation of Adaptive Difficulty Proportional Reasoning Game for Children

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Scalebridge: Design and Evaluation of Adaptive Difficulty Proportional Reasoning Game for Children

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***Abstract*—We present the design and evaluation of *Scalebridge*, an educational game that teaches children the mathematical skill of proportional reasoning. We also propose an adaptive level difficulty model that uses low-cost brain-computer interface device to modulate difficulty of the game based on the player's focus. We show that the game achieves the educational learning outcome of developing proportional reasoning skill both in the adaptive and in the non-adaptive version of game.**

***Index Terms*—game design, educational game, proportional reasoning**

Introduction

Proportional reasoning is an ability to think about numbers in relative, rather than absolute terms. It is essential cognitive skill for everyday tasks such as balancing scales or comparing prices per weight. However, proportional reasoning is an acquired rather than inborn ability. It should be learned between ages seven and ten [7] . Ten-year-old children find it difficult to invent proportional reasoning rules, if not previously taught. At the same time, children as young as seven can be effectively taught proportional reasoning.

Due to its importance in everyday life as well as mathematical development, understanding the mental landscape of proportional reasoning has been an area of active research for over forty years [7]. Huizenga [3] identified proportional reasoning as an essential part of early development of mathematical skills. It is also known that children learn proportional reasoning faster if the tutoring process is not based on verbal instructions only, but allows to manipulate objects [5]. Mental disorders, such as Attention Deficit Hyperactivity Disorder, are inversely correlated with proportional reasoning abilities [6].

Can proportional reasoning be learned through play? To address this question, we implement and evaluate *Scalebridge*, an educational game designed to teach proportional reasoning. Additionally, we design and evaluate an adaptive level difficulty model that uses low-cost brain-computer interface device to keep the player engaged and the learning process effective. We evaluate the adaptive and non-adaptive version of the game in a formal experiment.

Fig. 1: Scalebridge game interface

Game Design

Scalebridge is a game designed for children between ages seven and ten. The game starts by presenting to a player a bridge that connects a road over a river (Figure 1). The game starts with a configuration of lego blocks on the left side of the bridge that results in the bridge being unbalanced. The player's goal is to exactly balance the bridge so that cars waiting on each side of the bridge can cross it. To do so, the player must drop lego blocks onto the right side of the bridge in a configuration that will exactly balance the left side.

There are five positions where lego blocks can be placed on the right side of the bridge. Lego blocks to be used rest on the platform near the deck of the bridge. Blocks can be selected and moved with drag&drop. Blocks change color from green to yellow when the player selects it with the mouse cursor. Once the block is dropped onto a specific position on the bridge (Figure 1), the block changes color to grey, indicating that it is no longer selectable. If the block cannot be placed in a specific position, it turns red and returns to its original position.

Scalebridge's game mechanics are based on concepts most children are already familiar with: "choose a lego block" and

Level	Mirroring[1]	Sum of Blocks	Description of Tasks within Level
L1	Yes	2-12	Distance constant; weight varies
L2	Yes	2-12	Weight on the left constant, distance varies, single items
L3	Yes	2-12	Weight constant, distance varies, may have multiple blocks on a single scale
L4	Yes	13-24	Weight and distance vary, may have multiple blocks on multiple scale positions
L5	No	25-36	Weight and distance vary, some positions blocked out so mirrored solution not possible
L6	No	37-48	Weight and distance vary, bigger sums of weights at different distances
L7	No	49-60	Challenge problems, blocks placed on both sides of scale fulcrum

TABLE I: Level's difficulty criteria

"put the lego block on top of another block" in order to "balance the bridge". The player uses the spare blocks by pointing at the block with the mouse and dragging it to a position on the right side of the bridge in order to balance it. The weight of each block is the same.

Each difficulty level consists of five balancing trials. A trial times out at 60 seconds. The timer is displayed at the top-left corner of the screen. The difficulty level is presented at the top-right corner (Figure 1).

The player plays up to 35 trials: a maximum of 5 trials per each 7 levels of difficulty. Trials within each difficulty level follow difficulty heuristics outlined in the Table 1, based on the prior research [1]. The difficulty consists of two aspects: the allowed actions, and the sum of blocks. The sum of blocks determines number of blocks that have to be used to balance the bridge. The larger the sum, the more blocks, in average, need to be used to balance it.

Adaptive Difficulty Model

The learning time required to acquire proportional reasoning ability through learning vary from individual to individual. Yet, in a non-adaptive version of the game, the players are required to progress through levels that may be too easy or to hard for them. This could result in player's lack of engagement. In order to keep the player in the state of flow [2], we propose an adaptive difficulty model that affects how a player progresses through the levels using information on their performance and focus/relaxation.

While the players of the NON-ADAPTIVE version of the game must play all 35 trials, the ADAPTIVE DIFFICULTY game allows some participants to skip some trials and thus progress through the game faster. Whether or not the player is allowed to skip a trial is a function of two factors:

- previous trial completion status
- focus of the player

In every level, we consider the status of the last three trails played. The completion status is either 'win', meaning the player balanced the bridge within 60 seconds of the play time, or 'loss' when the player was unable to balance the bridge within the allowed time.

We also measure the focus level of the player using Neurosky MindWave device, which is a low-cost brain-computer interface providing information on the current attention (focus) and meditation (relaxation) of the player.

The ADAPTIVE game progression conditions are the following (Figure 3):

Fig. 2: A study participant is playing *Scalebridge*

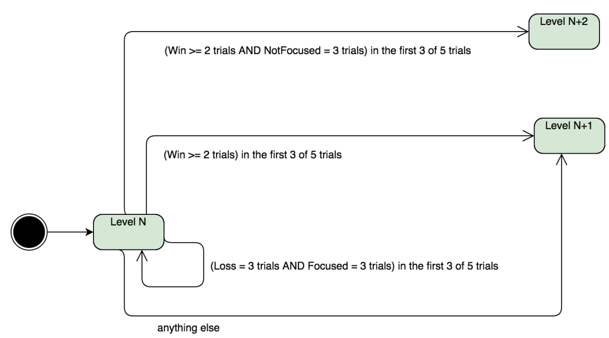

Fig. 3: Adaptive Difficulty Model

1) *Focused and winning (F/W) → go level up or progress to the next difficulty level*
   If the average Neurosky meter values during time play were 60 or more and the participant balanced the bridge within the available 60 seconds time play at least two times out of three consequent trials, this is considered a F/W situation that is counted toward fastest progression.
2) *Focused and losing (F/L) → the player will be shown an example 'how to balance' video and will be asked to finish playing the level.*
   If the average Neurosky meter values during time play

were 60 or more but the participant was unable to balance the bridge within the available 60 sec time play two times out of three consequent trials, this is considered a F/L situation and is not counted toward fastest progression. The player have to play trials 4 and 5 of the same difficulty level before progression to the next level.

3) *Not focused and winning (NF/W) → go two levels up or skip one difficulty level*
   If the average Neurosky meter values during time play were less than 60 but the participant balanced the bridge within the available 60 sec time play at least two times out of three consequent trials, this is considered a NF/W situation that is counted toward fastest progression.
4) *Not focused and losing (NF/L) → repeat the level*
   If the average Neurosky meter values during time play were less than 60 and the participant was unable to balance the bridge within the available 60 sec time play three consequent trials, this is considered a NF/L situation and is not counted toward fastest progression. The player is asked to repeat the level after three trials.

EVALUATION

In order to validate the game design, the study was conducted to investigate whether the ADAPTIVE game teaches proportional reasoning faster than the regular video game based on game completion time. We also evaluated whether the players enjoyed the ADAPTIVE video game more compared to the NON-ADAPTIVE group based on the subjective evaluation provided by the participants in the form of a flow questionnaire we designed based on [4].

Apparatus and Data Collection

The game was played on a PC computer (GTX 1080Ti, 16GB RAM, Intel i7 CPU, 27" monitor) with a mouse used as the game controller.

We collected the total number of trials required to finish the game and the time of completion of each trial. Additionally, each participant was asked to star-rate the difficulty of each trial after completion, on a 5 star scale, where 5 stars meant "the most difficult". The players were also asked to answer the questions in the post-game flow questionnaire to measure their enjoyment experience.

Participants and Procedure

We collected the data for 20 participants. At the beginning of the experiment, the participants were briefed about the experiment, and a short demonstration of the game was performed. The participants were randomly assigned to the ADAPTIVE group or the NON-ADAPTIVE group. Once assigned, a participant was seated in a chair in front of the computer. The mobile EEG-based headset (MindWave by Neurosky) with one electrode was placed on the participant's head. The headset's electrode was disinfected with an alcohol wipe prior to be put on the participant's head. The investigator then made sure the electrode is in proper contact with the forehead skin, and the ground-reference ear clip is properly placed on the earlobe of the participant. After the headset is in place, the investigator made sure the device is connected to the computer and the game to enable recording of brain activity. The participant then starts playing the game, beginning with the practice mode and transitioning into the experiment mode after 3 trials.

STUDY RESULTS

Overall, each participant spend in average 15.66 seconds (SD=4.31) on each trial completion. In the ADAPTIVE group, participants spent 16.38 seconds (SD=4.29) on the task completion; and in the NON-ADAPTIVE group participants spent in average 14.94 seconds (SD=4.43) on the trial completion. We also observed learning effect in the NON-ADAPTIVE group ($r_{10} = -0.72, p < 0.02$).

In general, all participants declared being focused on the game play. 19 participants evaluated their in-game concentration as "moderate", "fairly" or "extremely", and only one participant in the NON-ADAPTIVE game assessed their concentration as "slightly". None selected "not at all' concentrated option.

In addition to game experience or flow evaluations players completed at the end of the game, some of the participants provided verbal feedback about the game in the form of remarks. For example, one of the participants stated that he liked the idea that the game adapts to the player's attention, rather than the player "adapts attention" to the game . Another participant remarked that despite being an educational, the game did not not feel like "you were doing a homework".

DISCUSSION

We hypothesized that the players of the ADAPTIVE game will progress more quickly, as measured by the total number of trials played to achieve the end of game (and, thus, the proportional reasoning skill) and the total time (seconds) spent playing compared to the players of the regular video game. The analysis of time players spent on the trial completion over the period of the game play revealed a strong negative correlation between the total number of trials (M=38.8, SD=2.94) and the average time per trial (M=14.94, SD=4.43) in the NON-ADAPTIVE group , ($r_{10} = -0.72, p < 0.02$). The similar relationship trend between the total number of trials played (M=19.5, SD=5.04) and the average time per trial (M=16.38, SD=4.29) was noticed in the ADAPTIVE group, ($r_{10} = -0.55, p = 0.09$), although this correlation may need to be further investigated since it was not statistically significant. It is possible that the probability of the relationship between the variables in the ADAPTIVE group was not significant because participants played fewer number of trials compared to the NON-ADAPTIVE group. Since the players progressed faster in the ADAPTIVE game, their adaptation period to the more difficult level was not gradual, and consequently longer per trial, but shorter per gameplay.

The study results reveal the participants in both groups benefited from playing the game by acquiring the proportional

ADAPTIVE	Sum of Blocks	Subjective Difficulty Rating	Flow	Number of Trials	Trial Completion Time	Gameplay Time
A1	23.29	1.95	3.4	23	17.77	168.53
A2	25.61	1.89	2.4	20	16.12	119.28
A3	25.22	2.94	1.8	22	22.33	175.81
A4	24.83	2	1.8	13	18.08	95.06
A5	18.58	1.92	2.2	13	14.28	67.14
A6	24.42	2.33	2.4	14	18	81.3
A7	23.6	1.13	2	21	13.72	77.14
A8	22.76	1.1	0.8	29	10.19	80.14
A9	20.61	2.17	3.6	21	14.91	105.98
A10	16.8	2.33	1	19	8.95	58.69
NON-ADAPTIVE	Sum of Blocks	Subjective Difficulty Rating	Flow	Number of Trials	Trial Completion Time	Gameplay Time
B1	23.91	2.66	3.6	41	11.86	156.87
B2	23.83	1.43	2.8	39	15.3	192.13
B3	23.46	2.66	2.6	38	14.39	188.09
B4	23.63	1	0.4	43	12.22	161.4
B5	23.71	2	1.8	38	11.78	160.45
B6	23.66	1.94	2.6	36	11.61	163
B7	23.63	1	2	44	9.77	123.06
B8	23.94	2.2	3.6	36	18.46	267.52
B9	24.03	1.71	3.8	37	22.91	275.54
B10	23.54	3.54	3	36	17.85	248.46

TABLE II: Data collected in the experiment

reasoning skills as evidenced by completing the game. However, the NON-ADAPTIVE group participants learned slower as shown by entire game completion time, due to the need of completing all trials, even those that were ”too easy”. Thus, ADAPTIVE DIFFICULTY mechanism was shown to speed up the game completion process.

We hypothesized that players of the ADAPTIVE video game will enjoy the game play more than the players of the NON-ADAPTIVE game. However, no significant differences between the groups were observed in flow questionnaire scores, ($t_{18} = 1.12, p = 0.28$).

Although no statistically significant difference was revealed, in general, players of the ADAPTIVE game seemed less stressed based on our observation of them playing. Whereas the participants in the NON-ADAPTIVE group often asked during the game play how many more trials are left suggesting a little irritation and a feeling to finish playing.

Evaluation of Game Design

The presence of learning effect in the NON-ADAPTIVE group based on the strong correlation between the total number of games played and the average time spent on balancing the bridge confirmed that the game worked as designed - teaching proportional reasoning did occur. On the other hand, the learning effect suggests that ADAPTIVE version of the game may be more efficient, because the completion times per trial did not go down over the course of the game-play, possibly keeping the players challenged throughout the game.

The analysis of the in-game difficulty pointed to a number of game design modifications that might positively influence the results by improving confidence levels. For example, we would modify difficulty levels by increasing the spread between the levels by the number of possible sums of blocks within the previous level (e.g. level 1,2,3 - sums of 7 to sums of 15; level 4 - sums of 23 to sums of 31; level 5 - sums of 39 to sums of 47, etc.).

CONCLUSION

We presented *Scalebridge*, an educational game that teaches children the mathematical ability of proportional reasoning. We showed that the version of the game that used adaptive difficulty model taught proportional reasoning faster than non-adaptive game by avoiding unnecessary trails. In the future, we plan to improve the game's difficulty model and evaluate the game on children with Attention Deficit Hyperactivity Disorder, a condition that affects the acquisition of proportional reasoning ability.

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