A Teachable Agent Game for Elementary School Mathematics promoting Causal Reasoning and Choice

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Abstract: We describe a mathematics computer game for children designed to promote causal reasoning, choice-making, and other higher-order cognitive activities. The game consists of a choice-based board game, enhanced with a conversational, teachable agent, taught to play the game, by the child, through demonstrations and questions. Game design is motivated by causal reasoning theory and educational psychology. The game is currently evaluated in an ongoing large-scale study that seeks to investigate the game's effects on the players' abilities to reason and make productive choices. The study involves 20 elementary-school classes at different levels.

Keywords: Teachable agent, intelligent game, mathematics, elementary school, causal reasoning, choice, metacognition

1 Introduction

Educational games have documented potential effects on learning and motivation [1,2,3], but their delimitations regarding developed skills and competencies, attitudes towards a subject, and understanding of symbolic content are less understood [4].

The purpose of our research is to show that educational games are effective for the development of higher-order cognitive and metacognitive skills. The paper presents an educational game designed to develop such skills in the context of elementary mathematics, e.g., ability to reason over, reflect over, and invent strategies for solving mathematical problems. In the game, players take turns by choosing a card (representing a number) and placing it on a game board (also representing a number). The game challenge is to make as good as possible choices with respect to cards at hand and the game goal in question. Each card may yield points and its strategic value depends on the situation, so the choices give opportunity to reason. We have found the game to give substantial training of *causal reasoning* and *choice* which are basic cognitive processes that underpin all higher-order activities [5], and which are regarded as essential to train by educational psychologists [3]. Empirical research on instructional methods for supporting causal reasoning is scarce [5].

The game relies on two threads of research: the "Squares Family" microworld for understanding arithmetic concepts of the author [6]; the teachable agent of Biswas, Schwarz et al. [7,8]. The first version of the game was developed in 1998 and fieldtested in schools in 1999. The game presented in this paper is the result of a decade of evaluation and evolution of the initial game using an iterative, user-centric approach to development. The most recent addition is a teachable agent that starts out with no knowledge about mathematics but which has a built-in ability to learn it from the child, using the teach-by-guidance model [9]: the agent learns by observing the child's game playing behavior and by posing reflective questions about the choices. In this way, the teachable agent paradigm provides *structural guidance* and *reflection techniques* [10] known to help learners achieve deep understanding [11,12,13,4].

We are currently conducting large-scale studies of learning and motivational effects of the game using experimentation, observation, and inquiry in situations where students play the game as part of their regular education. Experiments involve playing and control conditions with pre-post tests, and game log analysis. Observations are concerned with behavior and social interaction in-class. Inquiries are concerned with end-user perceptions and attitudes towards the game. The game was evaluated in 9 classes in 2009, and is being evaluated in 20 classes during 2010.

The paper's focus is on the *design of a conversational, teachable agent as a mean to stimulate causal reasoning and productive choice strategies.* The agent presented has undergone several iterations of field tests to become "smart enough" to learn game playing strategies discovered by children. The contribution over past research [9] is a *knowledge model* that also involves *choice-strategy knowledge* and a *reasoning-oriented dialogue* based on that model.

2 The Teachable Agent Math Game

The game environment consists of combined card and board games, with a variety of levels and goals. We illustrate it by a few steps from a simple game (see Figure 1):

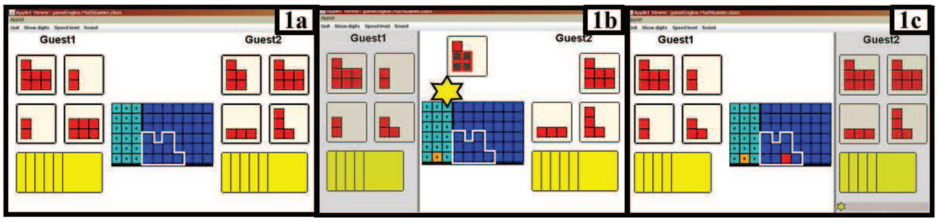

Fig. 1. Game play scenario: start (1a), during 2nd turn (1b), after 2nd turn (1c)

Two players on each side of a common game board receive 10 cards each: 4 face-up; 6 face-down. In Fig 1a the left player has received the cards 7, 2, 2 and 6 and the right player 5, 7, 3 and 4; the game board is empty and represents 0. The left player starts by choosing card 6 (bottom-right), causing 6 squares to be added to the board (not shown). The right player then chooses the card 5 (top-left of her cards), which causes a packing operation: 10 (i.e. 6+4) squares are packed into a *square-box* which is then placed in the board's leftmost compartment; the right player is awarded a point indicated by a flashing star (Fig 1b); in the same turn, the remaining square is placed on the board (Fig. 1c). This has illustrated that 6+5=11.

How well did the players do in this scenario? A better first choice for the left player would have been the card 2, since the right player's largest card is 7, and thus not enough for a carry-over: choosing 2 would have blocked the right player from scoring; further, choosing 2, neither of the right player's cards would have prevented the first player from scoring. Could the right player have made a better choice than 5, when the game board was 6? Three of the original cards would score (4, 5 and 7) whereas 3 would not so that 3 would have been a bad choice. However, card 4 is slightly better than 5, since 6+4 is 10, and no 1-digit number would yield a carry-over when added to 10. In this particular scenario the left player cannot score in either case with a board of 10 or 11, but keeping the 5 instead of the 4 might make a difference in later turns.

Already in this simple game, making good choices involve reasoning on several levels. Other games are more challenging: 3-digit cards can generate between 0-3 points per turn, and each digit in the result may allow or block the opponent to score in that position. There are games that include negative numbers, other operations than addition and have goals that are more difficult to fulfill than carry-overs. Players can choose to either compete or collaborate, and the strategies for playing well differ.

2.1 The Conversional Teachable Agent

Besides playing self, children can teach an agent how to play and watch the agent play. The agent performs according to its current knowledge level, which depends on how well it is taught. There are two ways to teach: by showing the agent how to play (show-mode); by letting the agent try and then accept or reject the agent's choice (try-mode). In both modes the agent will ask multiple-choice questions to its teacher, concerning the choice(s) just made (see Figure 2a).

The questions asked depend on several factors: the game's state (the chosen card, the board, and the players' hands), the teaching mode, whether players compete or collaborate, and the agent's current knowledge level.

The agent's knowledge level is estimated from a trace of the child's actions and from a record of her responses, as is explained in [9]. The general idea is that we keep track of positive indications (scoring rules and strategic values of chosen cards or correctly answered questions) as well as negative indications (missed rules in better choices or incorrect answers) and calculate a knowledge level from these indications.

Our current model includes knowledge in five categories 1) the game idea, 2) how the graphical model behaves, 3) how to score, 4) how to choose the best card considering own cards, and 5) how to choose the best card considering the other player's cards too. Categories 1-3 represent mathematical knowledge; while 4-5 represent strategic and choice-making knowledge.

During the game, the agent's knowledge is shown using 5 knowledge meters (see Figures 2b, 2c, 3d and 3e). Taken together, the knowledge meters reflect a progression in *sophistication of choice*: from knowing what the game is about, to consideration of all possible paths 2 steps ahead.

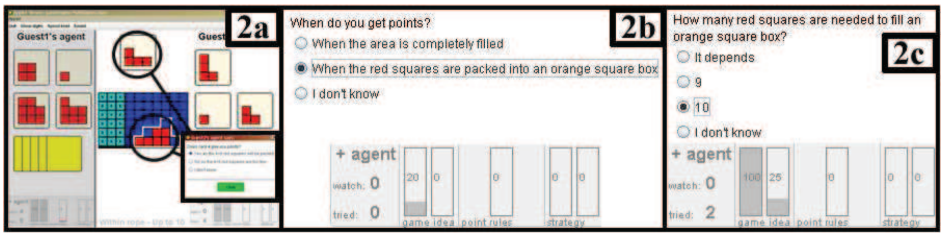

Fig. 2. Game UI (2a), game idea question (2b) and graphical model question (2c)

Questions difficulty level advance with the agent's knowledge. The simple question in Figure 2b is asked when the agent knows very little (the meters are low) and the more difficult question in 2c, later in the game, when the agent knows more. Questions are chosen to be slightly above the agent's knowledge level to allow progression towards the child's level; when the child's level is reached, the child is challenged by reflective questions. If progression stops, so will the advancement of questions. This follows the idea of Vygotskij's zone of proximal development [14].

Fig. 2 gives examples of advanced questions. Question 3a is from show-mode, where the child has chosen a card and the agent has made a hypothetical choice according to its knowledge, which is reflected in the question: "I also thought of card 4..." (the agent's choice was the same as the child's). Question 3b is from try-mode, where the child accepted the agent's choice: "So I made a good choice, right?" Question 3c occurs in either mode, and compares the child's and the agent's choice: "Why is card 2 better than card 4?". Alternative responses reflect the choice sophistication level: being able to distinguish between 1) different scores, 2) general strategic value of same-score cards and 3) situation-specific strategic value of same-score cards. Question 3d is raised when the agent's scoring knowledge is high (the middle meter is almost full), so the question considers both scoring and the strategy to leave few squares (general strategy). Question 3e is the most challenging type of questions which involves both scoring and blocking the opponent in the next turn (situation-specific strategy). To be sure of the correct response: "It's obviously the best one! It gives 1 point and it's the only card that blocks the opponent", the child must predict and distinguish between 16 alternative paths: each own card composed with any of the opponent's cards.

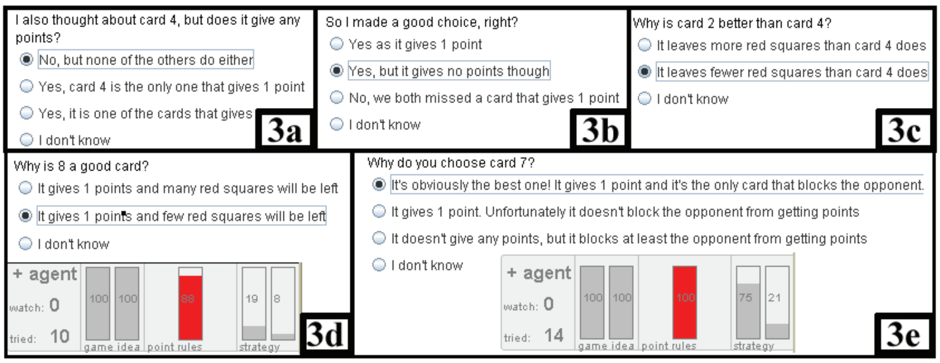

Fig. 2. Five examples (3a-3e) of questions from scoring and strategic categories

Our approach is related to the programming by demonstration principle [15,16] in the sense that the user demonstrates examples of desired behavior and the system generalizes the examples to rules. However, the agent-teaching extends the principle with reflective dialogue, it targets mathematical and strategic knowledge rather than programming, and the agent can perform (i.e., play the game) at any knowledge level.

3 Promoting Causal Reasoning and Choice

Our game is designed to promote causal reasoning and choice. In particular, it fosters the following sub-forms of causal reasoning identified by Jonassen and Ionas [5]: *prediction*, *implication*, *inference,* and *explanatory explanations*.

Prediction is defined as reasoning about possible future states on the basis of a given set of states and possible effects. Players of our game need to predict the effects of cards regarding point generation and strategic value (to play well).

Implication is defined as hypothesizing state-effect relationships. Players of our game do not know how cards score a priori, but successively discover this through hypothesizing the cards' effects on the score (while making the choice), and by observing the played card's actual effect (once the choice has been made).

Inference is defined as backwards reasoning from effect to cause. This form of reasoning occurs when a player starts from a game goal (e.g., producing a carry-over in a compartment), then decides what is needed (e.g., a card greater than or equal to 7), and finally checks for a matching of such card at hand.

Explanation in this context is defined as being able not only to induce causal relations, but also to explain them. Players of our game are prompted with reflective, explanatory questions of the agent, and thereby encouraged to reason about and verbalize *why a choice is good*.

Our game fulfills Jonassen and Ionas's recommendations on using *explorations in microworlds* and *explanatory questions* as means of achieving such reasoning skills [5]. The game relies on a microworld of arithmetic; the agent's interaction with the user relies on questions in which the child explains her choices in relation to alternatives.

The ability to make good choices is fostered by the game as a whole: the incentive of the causal reasoning, illustrated in the examples above, is to make good choices; good choice is the only way to perform well in the game. Our notion of good is captured by a context dependent *goodness value* for each possible card. The goodness value reflects the card's score and its strategic value, and is used in the assessment of the player's level of knowledge.

4 Discussions and Future Work

Schwartz and Arena argue that *choice-making* will be an important skill in the 21st century that should be practiced and assessed in education [3]. Our game gives opportunity to practice choice-making in a playful way, within a well-defined domain (arithmetic) with immediate feedback and progress, and with few choices (four cards).

Guided learning has repeatedly been shown to be superior to unguided learning [13]. The teachable agent provides implicit guidance through reflective questions that direct the player's attention to discriminating properties of the choices: each choice is assessed to give a goodness value; this allows us to study progression of choice-making, and players to value their performance (irrespective of their luck with cards).

Observations and previous studies [17] show that children quickly learn to play well, but that the degrees to which they challenge themselves vary. This is a matter of motivation; and teachable agents have increased motivation in other contexts [18].

With our new agent and with extrinsic incentives (medals, meters, high-scores, and statistics) we hope to motivate students to further engage in learning productive choice strategies. This is investigated in our current study: i.e., players' abilities to reason and make productive choices, progression paths, choice-patterns, and learning- and motivational effects compared to traditional mathematical instruction.

Finally, we think that our game mediates that mathematics is not merely a matter of right and wrong – computation is – but mathematics is much more than computation.

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