South Bohemia Mathematical Letters
Volume 31, (2023), No. 1, 36–43.

THE ROLE OF EDUCATIONAL GAMES AS AN INSTRUCTIONAL CONTEXT TO PROMOTE EXECUTIVE FUNCTION PROCESSES IN MATHEMATICS EDUCATION

DAVID C. WEBB

ABSTRACT. Overt disruptions to schooling that occurred during the COVID-19 pandemic motivated educators to re-examine normative classroom practices and give greater attention to students' interests, engagement, and sense of belonging. The use of games by mathematics teachers has often been viewed as a way to provide a break from normative mathematics instruction and increase student engagement. This paper examines the games as an approach to promote student engagement and executive function (EF) processes in mathematics education. Three core EFs –working memory, cognitive flexibility, and inhibitory control – are analyzed for two mathematics games. Issues related to the explicit integration of EFs in mathematics education using games are also discussed.

1. INTRODUCTION

Much attention has been given to online gaming and the emergence of esports as an extra-curricular activity promoted by schools and community organizations. However, non-digital games have had a role in mathematics education for decades, as a diversion from routine activity, as a way to build community, and as an end-of-unit review activity, among other purposes. From first-hand experience as a secondary mathematics teacher, when "it's time to play a game" was offered to the class, the result was an immediate shift in the enthusiasm of students with overt expressions of excitement and eagerness. Even though students understood the game would involve the use of mathematical knowledge and reasoning, their collective enthusiasm toward playing the game was not dampened.

1.1 DESIGNING ACTIVITIES INTEGRATING EXECUTIVE FUNCTIONS AND MATHEMATICS

Over the past three years, the Spark Math project team has explored the use of games as an approach to promote and develop executive function processes alongside mathematics education goals. The underlying goal of this research report is to examine the role of educational games vis-à-vis research in executive functions (EFs) and to identify aspects of games that support EFs and mathematics education. Awareness of intersections between games, EFs, and mathematics may inform the design of professional learning activities for teachers to advance their awareness of how EFs are elicited and advanced in various instructional contexts. Such awareness could also inform the design and use of instructional resources for students. Recently developed games that we have observed in classrooms with middle grades mathematics teachers and their students will be used to illustrate how games were used to enhance student and teacher awareness of and reflection on EF processes in mathematics education. Before discussing the

Received by the editors: 10.02.2024.
2020 Mathematics Subject Classification: 91A12, 97C30, 97U60.
Key words and phrases. Mathematical games, executive functions, inhibitory control, Working memory, cognitive flexibility.

role of games and EFs in mathematics education, it is important to describe how a game is defined and interpreted within the scope of this paper.

1.2 GAMES AS AN INSTRUCTIONAL CONTEXT

Many definitions for games have been offered in scholarly and industry literature (e.g., Huizinga [1944/1955], Caillois [1958/2001], Crawford [2003], Tekinbas & Zimmerman [2003], Klabbers [2009], Koster [2014], etc.). Juul (2010) considers many of these historical and contemporary definitions for a game and summarizes this multi-dimensional construct as,

> A game is a rule-based formal system with a variable and quantifiable outcome, where different outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable (p. 255).

The selection of Juul's (2010) definition is based on his identification of a game as a rule-based system with varied (and unpredictable) outcomes. Games are activities that require effort (i.e., authentic engagement) by players, and the players have some interest in the outcome. However, one other important characteristic not mentioned by Juul (2010) is the social dimension of interactivity. As noted by Crawford (2003), interactivity is a continuous dimension that can involve competition, teamwork, or collaboration. Collectively, these characteristics are important features of educational games designed for use in classrooms by groups of students.

To further narrow the definitional boundaries, not all games are educational. On the other hand, through positioning, prompting, adaptation, and/or reflection, some games can be repurposed to have (math) educational value. Kloep, Helten and Peifer (2023) described the combination of learning content with game-like contexts as educational games, or serious games. An example of a serious game for mathematics could be an adaptation of Tic-Tac-Toe.

FIGURE 1: A serious game of Tic-Tac-Toe

Starting with its familiar rules, the large hashtag game board for Tic-Tac-Toe in Figure 1 is adapted by including integers that are the result of products of a set of factors that each player must use. Game mechanics are adapted so that the next player selects a factor from their set of integers that, when multiplied by the factor played by the previous player, creates a product found on the game board. In this example, game rule familiarity is leveraged to create a context for using mathematics to play the game and make strategic decisions about the best move.

1.3 Executive Function Processes

Since EF processes are used by individuals to suppress distractions to engage in a task, engage in memory retrieval and updating, and shift between different procedures and concepts (Bull & Lee, 2014; Cragg & Gilmore, 2014), a cognitive psychology perspective is used as a theoretical lens for interpreting the role of EFs in mathematical games (Verschaffel, van Dooren, & Star, 2017). As described by Diamond and Lee (2011), EFs are cognitive control functions. Cragg and Gilmore (2014) defined EFs as "a group of processes that allow us to respond flexibly to our environment and engage in deliberate, goal-directed, thought and action" (p. 64).

Over the last 20 years, theorizing about EFs has included the categorization of hot and cool EFs (Zelazo & Muller, 2002). Cool EFs are processes that are utilized when engaged in non-provocative academic activities, such as solving a set of multi-step problems. Cool EF processes such as working memory, cognitive flexibility, and inhibition are utilized at some point depending on the level of challenge of the set of tasks in relation to the learner (Bull & Lee, 2014). Hot EFs are more emotionally laden and include processes such as impulse control, managing emotions, and delayed gratification. Even though cool EFs have been studied as predictors of academic success, Welsh and Peterson (2014) noted that "most would agree that achievement of high school and college demands both cold cognition and hot emotion regulation abilities" (p. 57).

The three core EFs identified by Diamond and Lee (2011) – working memory (WM), inhibition, and cognitive flexibility (CF) – are cool EFs that have been associated with the recall of mathematical objects, strategic competence, and problem solving. In analyzing how EFs contribute to mathematics achievement, Bull and Lee (2014) identified age as contributing to variance in EF structure and noted that while updating (WM) is a strong predictor of mathematics achievement across age groups, findings for switching (CF) and inhibition were mixed.

1.4 Executive Functions and Game Play

Cognitive flexibility, or shifting, involves flexible switching between tasks and procedures (Cragg & Gilmore, 2014) and shifting between different strategies and representations, as needed (Bull & Lee, 2014). Tasks that are open to multiple solution strategies or multiple representations are more prone to engage and develop learners' cognitive flexibility. Serious math games can be designed to leverage switching by including mathematical representations that can be interpreted in multiple ways. Rules for games also influence opportunities for shifting. As argued by Koster (2014), "Fun comes from 'richly interpretable' situations…. the more rigidly constructed your game is, the more limited it will be." (p. 38; author's emphasis).

Inhibitory control involves "suppressing distracting information and unwanted responses" (Cragg & Gilmore, 2014, p. 64). Bull and Lee (2014) exemplified inhibition in mathematics education as suppressing inappropriate strategies, representations, and relationships (p. 37). Games can be designed to enhance inhibition by invoking rules that have consequences, such as "once a card is played, it cannot be taken back from the discard pile." Inhibition often goes hand-in-hand with observing the moves of previous players, considering options, and making the best play. Suppression of distractors during a game may include ignoring teasing by other players, and other conversations in the classroom. Huizinga (1958) and others have theorized gameplay as creating a magic circle, "a special place in time and space created by a game" (Tekinbas & Zimmerman, 2003, p. 95). As such, the shared understanding of what a game entails within a classroom can provide implicit support for inhibition – "Don't interrupt! They are in the middle of a game."

The well-studied EF process of working memory involves the storage and retrieval of relevant information, and Bull and Lee (2014) define updating as "monitoring and the addition or deletion of contexts from WM" (p. 36). Given the prevalence of symbols, abstractions, and procedures in mathematics, it is not surprising that updating WM is a strong predictor for mathematics achievement (Cragg & Gilmore, 2014; Bull & Lee, 2014). Serious games are a productive context for engaging working memory. To play a game, typically rules are established. All players must agree on the interpretation of the rules to recognize what can and cannot be done by a player during each round. As each round is played, players have an opportunity to observe and experience how these rules are applied. As gameplay strategies are understood, players will mentally retrieve and update multiple cycles of options for their next move, while observing how the moves of other players impact their choice of the best play.

2. Approach and Analysis

Regarding the analysis of tasks as a proxy for potential student reasoning elicited, Neubrand et al. (2013) assert that students

> … are often introduced to lesson content through tasks, they see their mathematical activity in terms of their engagement with tasks, and they experience competence in solving those tasks. Tasks thus provide the basis for students' cognitive activities (pp. 126-127).

To evaluate the extent to which serious games can elicit and promote EFs, an interpretive task analysis process is used with the previously introduced Integer Product Tic-Tac-Toe and a card game designed by the Spark Math team, Equivacards. Even though I was a member of the Spark Math project team, I was not a co-designer of the card games. My project role included the facilitation and observation of gameplay with educators as part of their professional development experience, and observing teachers use these card games with students in their middle grades classrooms (ages 10 – 13). Observations of educators and students were used to inform the illustrations and analysis of both games. Key representations and rules for gameplay are presented, followed by task analysis focused on their respective potential for eliciting and engaging players in the EF processes of working memory, cognitive flexibility, and inhibition.

Both games are multiplayer. Integer Tic-Tac-Toe involves interaction between a pair. Equivacards typically involves a group 4 to 6 of students. Initiation of gameplay creates a context (i.e., "magic circle") for players to engage in strategic-mathematical tasks. As players become familiar with the rules and tasks involved in a round of play, game-related schemas may emerge that are refined by observing other players' moves and interpreting supportive and/or corrective feedback. Resulting reasoning for each player may be supported by WM, CF, and inhibitory control.

2.1 Integer Product Tic-Tac-Toe: Gameplay and analysis

This game requires the use of a large hashtag board with nine different products and a set of integers for each player (see Figure 1). The rules are as follows:

a. Player 1 is represented by the square. She chooses a number from her set (assume -2) and crosses it out. Note: The first play is never marked on the gameboard since -2 is only one factor and needs another factor to make a product.
b. Player 2 chooses a number from his set, -3, and crosses it out from his set. He multiplies the -3 he selected by -2, the last number chosen by Player 1. Since 6 is the product, he puts a circle around the number 6 on the gameboard. (Note: You do not have to make a play on the board every time you choose a number).
c. Player 1 chooses an unmarked number from her set, 1. She crosses it out and multiplies 1 by -3, the last number selected by Player 2. She says the product is - 3 and places a square around – 3 on the game board. Play continues, with each player choosing an unmarked number from their set and multiplying it by the last number selected by

previous player until there are three squares or circles in a row, all numbers on the gameboard are taken, or all numbers in the players' sets are used.

Working Memory: When students were asked to share their reasoning after several rounds of play, most described thinking through the remaining products that could be generated by their set off the last factor played. The mathematical tasks generated for each player were the recall of multiplication facts and sign rules for multiplying integers. Early in the game, some students wrote down resulting products on paper which faded when fewer numbers were in play. Opportunities for updating were informed by the best plays remaining on the gameboard.

Cognitive Flexibility: With this game, flexibility with math representations is limited: all factors and products are integers. To increase opportunities for flexibility with mathematics, different types of rational numbers (e.g., fractions, decimals) could be used for the board and player sets. Cognitive flexibility was expressed with strategic gameplay. As students gained experience with the game, they recognized that playing a 0 or 1 was advantageous (e.g., playing the 0 first would capture the middle space and force the other player to miss a play since they would have to play off 0 as a factor).

Inhibition: Apart from the need to limit verbal distractions from other tables, this EF emerged in later rounds of the game when player sets had fewer factors to choose from and few products left on the game board. Rounds would slow down as players would think through all the different options that remained (updating), cycle through all of the outcomes, and reluctantly select a factor to play. In later rounds of the game, as the sample space reduced, inhibitory control appeared to increase.

2.2 EQUIVACARDS: GAMEPLAY AND ANALYSIS

This game is played with a deck of cards. As shown in Figure 2, cards numbered from 1 to 8 and six algebraic expressions (x, x + x, 2x, x + 1, x + 2, 9 – x) are colored green, red, yellow, and blue. White cards determine the value of x, which can be 1 through 4. Each player is dealt 7 cards.

FIGURE 2: Equivacards

Gameplay is modelled after Uno™ and the winner is the first to have no cards left in their hand. Other rules for gameplay are as follows:

a. The card on the top of the deck is turned over and starts the pile. White cards are played off to the side. The value of *x* remains 1 until a different white card is played.
b. The player left of the dealer plays a card that either matches the color or value of the card face up on the pile. If that player does not have a card that matches the color or value, or does not have a white card to play, a new card is drawn, and their turn ends. After playing a card, the player may continue to play cards until they have no more matches (i.e., a run of matches).
c. White equation cards (*x* =) can be played anytime during a turn. After being played, the new value of *x* is in effect until another *x* = card is played.
d. Play continues counterclockwise until one player has no cards left in their hand.

Working Memory: Players were observed organizing cards in their hands to match the value or color as their turn neared. When prompted, most described silent iteration of color or value (e.g., green or 4) that could be played, especially when an expression card or an x = card was played. Play of expression or white "x =" cards created opportunities for updating. No written work was observed.

Cognitive Flexibility: The mathematical tasks included basic arithmetic and evaluating expressions for a given value. Flexibility with math representations occurred with expressions and values. Players switched between the algebraic expression and value, and often pointed out equivalent expression cards – e.g., "x + x is the same as 2x," or "x + 2 is the same as 2x when x equals 2." Flexibility with strategic gameplay was observed when players created sequences of cards in their hands that could be played as a run of matches.

Inhibition: Some "encouragement" (or heckling) occurred when players would take too long to take their turn. Potential inhibitory control was also observed for players who focused on making a run of matches and/or the winning play, and not playing cards to create extended runs. The penalty of selecting another card or feedback from players about an incorrect play likely enhances inhibitory processes.

3. Discussion

The purpose of this paper was to examine the role of educational games in supporting EFs in mathematics education. Numerous scholars have documented the close association between mathematics education and EF processes. In addition, a long history of research on approaches to developing EFs (Katz, Shah & Meyer, 2018) suggests the importance of intentional design and focus on specific EFs in video games (e.g., Mayer, Parong, & Bainbridge, 2019). The same principles likely apply to non-digital games such as those discussed here.

Non-digital games can provide a unique, playful context for pairs or groups of students to motivate EFs in a way that typical classroom practices in math education do not. Munakata and Doebel (2021) identified the importance of play and less structured time for the development of EFs, and argued, "Less-structured time can also provide opportunities to observe, learn from, and engage with others" (p. 28). In their review of EF research, Munakata and Michaelson (2021) also noted that many studies "highlighted the potential of a rich interplay between social context and executive function development" (p. 151).

At a more practical level, when observing EF processes in games how should teachers discuss EFs with students? EFs should be recognized as student assets that are worth sharing and discussing. Allocating classroom time to discuss student reasoning in mathematics education could enhance students' meta-cognition and help them recognize the benefits of self-regulation. At the very least, students could describe strategies for supporting their working memory, share different strategies and mathematical representations that they use, and enact inhibitory control processes in their terms. Then the teacher can decide if or when it is appropriate to relate students' examples and informal language to the formal terms described in research on EFs.

*Acknowledgements***.** Equivacards was thoughtfully co-designed and piloted by Ben Katz and the Spark Math project team, enthusiastic project teachers, and their students who were always eager to play. This research was supported, in part, by funding from the EF+Math Foundation. Any opinions, findings, or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the funder.

REFERENCES

[1] Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives*, *8*(1), 36-41.

[2] Caillois, R. (1958/2001). *Man, play, and games* [trans by M. Barash]. University of Illinois Press.

[3] Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in neuroscience and education*, *3*(2), 63-68.

[4] Crawford, C. (2003). *Chris Crawford on game design*. New Riders.

[5] Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science*, *333*(6045), 959-964.

[6] Huizinga, J. (1944/1955). Homo ludens; a study of the play-element of culture. Boston: Beacon Press.

[7] Juul, J. (2010). The game, the player, the world: Looking for a heart of gameness. *PLURAIS-Revista Multidisciplinar*, *1*(2), 248 - 270.

[8] Katz, B., Shah, P., & Meyer, D. E. (2018). How to play 20 questions with nature and lose: Reflections on 100 years of brain-training research. *Proceedings of the National Academy of Sciences, 115*, 9897–9904.

[9] Klabbers, J. H. (2009). The magic circle: Principles of gaming & simulation. In *The Magic Circle: Principles of Gaming & Simulation*. Brill.

[10] Kloep, L., Helten, A. L., & Peifer, C. (2023). A Playful Way to Promote Team Flow: Evaluation of a Positive Psychological Board Game for Team Building. *International Journal of Applied Positive Psychology*, 1-23.

[11] Mayer, R. E., Parong, J., & Bainbridge, K. (2019). Young adults learning executive function skills by playing focused video games. *Cognitive Development*, *49*, 43-50.

[12] Munakata, Y., & Michaelson, L. E. (2021). Executive Functions in Social Context: Implications for Conceptualizing, Measuring, and Supporting Developmental Trajectories. *Annual Review of Developmental Psychology*, *3*, 139-163.

[13] Munakata, Y., & Doebel, S. (2021). Developing executive functioning through less-structured time. *Science*, *374*(6563), 27-28.

[14] Neubrand, M., Jordan, A., Krauss, S., Blum, W., & Löwen, K. (2013). Task analysis in COACTIV: Examining the potential for cognitive activation in German mathematics classrooms. In M. Kunter, J. Baumert, W. Blum, U. Klusmann, S. Krauss, & M. Neubrand (Eds.), *Cognitive activation in the mathematics classroom and professional competence of teachers: Results from the COACTIV project* (pp. 125-144). Springer.

[15] Tekinbas, K. S., & Zimmerman, E. (2003). *Rules of play: Game design fundamentals*. MIT Press.

[16] Welsh, M., & Peterson, E. (2014). Issues in the conceptualization and assessment of hot executive functions in childhood. *Journal of the International Neuropsychological Society*, *20*(2), 152-156.

[17] Verschaffel, L., Van Dooren, W., & Star, J. (2017). Applying cognitive psychology based instructional design principles in mathematics teaching and learning: introduction. *ZDM*, *49*, 491-496.

[18] Yackel, E., & Cobb, P. (1996). Sociomathematical norms, argumentation, and autonomy in mathematics. *Journal for research in mathematics education*, *27*(4), 458-477.

[19] Zelazo, P. D., & Muller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development*. Oxford: Blackwell Publishers.

UNIVERSITY OF COLORADO BOULDER
BOULDER, COLORADO, USA
E-mail address : dcwebb@colorado.edu