Activating Adolescents' "Hot" Executive Functions in a Digital Game to Train Cognitive Skills: The Effects of Age and Prior Abilities

Bruce D. Homer, Jan L. Plass, Maya C. Rose, Andrew MacNamara,
Shashank Pawar, & Teresa M. Ober

Published in 2019 in *Cognitive Development*, 49, 20–32.
Link to Peer-Review Process

Abstract

Executive function (EF), critical for many developmental outcomes, emerge in childhood and continue developing into early adulthood (Blakemore & Choudhury, 2006). During adolescence there are important developments in *Hot EF*, which involves using EF in emotionally salient contexts (Zelazo & Carlson, 2012). The current study used an *emotional design* approach (Um, Plass, Hayward, & Homer, 2012) to study hot EF in adolescents playing a digital game designed to train the EF subskill of shifting. Participants (N = 233; aged 12 to 16, M = 13.8, SD = 1.1) played one of two version of the game: *hot* (with emotional design), or *cool* (with more emotionally neutral design). There was a main effect of condition, with higher posttest scores on shifting in the hot condition. Condition significantly interacted with age: older adolescents had better outcomes in the hot condition than in the cool condition. A three-way interaction between age, prior EF and condition was found, indicating that the age by condition interaction was affected by prior EF. These results indicate that the higher emotional arousal in the hot condition is more effective for enhancing EF skills, particularly for older adolescents, and argue for developing learning and training games that account for developmental changes such as the growth of hot EF in adolescence.

Activating Adolescents' "Hot" Executive Functions in a Digital Game to Train Cognitive Skills: The Effects of Age and Prior Abilities

Executive Function (EF) refers to a set of related cognitive processes that allow for the planning, monitoring and control of cognition, behavior and emotions in order to remain goal-oriented (Best & Miller, 2010; Diamond & Lee, 2011). EF first emerges in early childhood and continue to develop throughout adolescence into early adulthood (Blakemore & Choudhury, 2006). Although tied to specific brain developments, environmental and experiential factors have been shown to have a great influence on the development of EF. For example, the stressors of poverty have been associated decreased EF in preschool children (Blair et al., 2011; Blair & Razza, 2008; Sarsour et al., 2011). These disparities in early EF may contribute to the achievement gap that continues to widen over time (Finn et al., 2016; Noble, McCandliss, & Farah, 2007; Ryan, Fauth, & Brooks-Gunn, 2006; Welsh et al., 2010). Conversely, numerous approaches have been identified that support the development of EF, including explicit classroom curricula, martial arts training, and digital interventions (Diamond & Lee, 2011). Interest in finding ways to improve EF is driven by the considerable evidence of the importance of EF for a number of behavioral and developmental outcomes in children and adolescents (Blair & Razza, 2007; Miller & Hinshaw, 2010; Welsh, Nix, Blair, Bierman, & Nelson, 2010).

Most successful EF interventions share two common features: repeated practice and activities that become progressively more challenging (Diamond & Lee, 2011). Even though computerized interventions, including digital games, have both of these features, evidence for the effectiveness these types of interventions has been mixed. Although some reviews have found that digital games have had limited success in training EF (e.g., Mayer, 2014; Powers, Brooks, Aldrich, Palladino, & Alfieri, 2013), other recent studies have found that some digital games can be effective tools for supporting the development of EF (Anguera et al., 2013; Homer, Plass, Raffaele, Ober, & Ali, 2018; Parong et al., 2017). Given that only some digital trainings of EF are effective while others are not, it is of both practical and theoretical importance to identify the specific features that can make digital games effective tools for learning and cognitive skills training (Plass, Homer, & Kinzer, 2015).

The goal of the current study is to examine the effectiveness of developmentally informed features of a game created to support the development of EF in adolescence. The premise is that matching design features to relevant developmental factors will help make a digital game-based intervention more effective. Specifically, in consideration of developments in *Hot EF* (Zelazo & Carlson, 2012) that occur during adolescence, we investigate the use of an *emotional design* approach (Plass, Heidig, Hayward, Homer, & Um, 2014) to make a digital game intended to train the EF subskill of shifting more appropriate for older versus younger adolescents. To understand best how to create a developmentally appropriate game design for adolescents requires first considering the developmental trajectory of EF, including relevant neurophysiological changes.

The Development of Executive Functions

Although there is variation in how the specific components of EF are characterized, one of the most widely accepted approaches is Miyake and colleagues' *Unity and Diversity* framework (Miyake et al., 2000). In this framework, EF involves sub-skills that are related to one another (i.e., unified) but are also statistically distinct, differentially predict performance on cognitive tasks, and manifest at different developmental periods (i.e., diverse). Subskills include *inhibition*, the ability to suppress behavioral or cognitive impulses, *shifting* (or *switching*), the ability to mentally shift attention between tasks, and *updating* (or *working memory*), the ability to hold and manipulate information in one's mind (Miyake et al., 2000). The EF components support development of more complex higher-order skills, such as planning and reasoning (Diamond, 2013; Ortner, Kilner, & Zelazo, 2007; Zelazo & Lyons, 2011)

EF first clearly emerges around 24 months of age, with additional rapid developmental change between the ages of 3 to 6 (Carlson, 2005; Jones, Rothbart, & Posner, 2003), and clear evidence of continued growth well into adolescence (Hughes, 2011). Although ages at which the subskills of EF reach adult levels are not absolutely determined, in part because of variation in performance on the specific tasks used to assess EF (see Best & Miller, 2010; Perone, Almy, & Zelazo, 2018), the pattern of development is fairly consistent. Inhibition appears to develop first and continues to develop in adolescence, with shifting and working memory developing later and not reaching a mature adult state until late adolescence or early adulthood (Davidson, Amso, Anderson, & Diamond, 2006; Huizinga & van der Molen, 2007). These developments may be reflected in behavioral difference. For example, when solving problems, younger children tend to rely more on inhibition, while older children and adolescents rely more on shifting and working memory (Davidson et al., 2006; Diamond, 2013; Huizinga, Dolan, & van der Molen, 2006; Isquith, Crawford, Espy, & Giola, 2005).

Most broadly, EF has been associated with activation in the lateral prefrontal cortex (PFC) within the cerebral cortex (Kane & Engle, 2002; Zelazo & Müller, 2002). During adolescence, beginning with the onset of puberty, there is an accelerated period of EF development that is marked by a linear growth in the amount of white matter in the frontal areas of the brain, likely reflecting an increase in neuronal myelination. At approximately the same time, the amount of gray matter changes with age in an inverted U-shaped pattern, reflecting synaptic pruning and further reorganization (Barnea-Goraly et al., 2005; Blakemore & Choudhury, 2006; Sowell et al., 2004). MRI studies have shown that gray matter may continue to steadily increase until puberty and then proceed to decrease from adolescence through early adulthood (Sowell et al., 2003; Sowell et al., 2001). The increased myelination during early adolescence results in increased speed of neuronal transmission, and the decrease in gray matter from synaptic pruning during later adolescence results in improved speed and efficiency of cognitive processing, including improvements in adolescents' EF (Best, Miller, & Jones, 2009; Davidson et al., 2006; Huizinga et al., 2006; Luna & Sweeney, 2004).

Although adolescents reach mature, adult-like levels of performance on some standard EF tasks (Huizinga et al., 2006), behaviors associated with impulsivity and risk-taking continue to be observed, especially in contexts that elicit an affective or emotional response (Leshem, 2016), such as when faced with peer pressure (Blakemore & Robbins, 2012). Researchers have attributed such conflicting behaviors (i.e., demonstrating mature EF skills in combination with risky-decision making) to the early development of subcortical regions responsible for emotions and motivation and the later development of the PFC (Blakemore & Robbins, 2012; Dahl, 2004). Further, the lack of impulse control and higher levels of risk-taking in adolescents may be attributed to the discrepant time-course of development of these brain structures (Steinberg, 2008). The ability to execute cognitive control in conditions of high motivation and emotion has been identified as "hot EF", which undergoes important developments during adolescence (Zelazo & Müller, 2002).

Hot EF and Cool EF Development

Although most EF research has focused on lab-based performance in emotionally neutral conditions, cognition is often different in emotionally laden situations (Bechara, 2004). To delineate EF processes in motivationally significant situations, and to identify reasons why adolescents' decisions do not consistently align with their objectives, researchers have distinguished between “hot EF” and “cool EF” (Perone et al., 2018; Welsh & Peterson, 2014; Zelazo & Müller, 2002). Cool EF refers to the top-down processes that are utilized in decontextualized and abstract situations that lack clear rewards, punishments or personal consequences. Measurement of such cool EF involves abstract, decontextualized stimuli such as those found as the flanker, n-back and Dimensional Change Card Sort (DCCS) tasks, in which participants are required to inhibit responding to arrows, numbers, or neutral shapes and colors. Hot EF refers to the top-down processes that are elicited in emotionally salient real-world contexts marked by clear rewards and personal consequences. Measurements of hot EF, such as the Iowa Gambling Task, are designed to evoke an emotional response (Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Zelazo & Carlson, 2012) by having “real world” consequences, such as participants winning or losing real items (i.e., money or candies). Hot EF is also involved in situations that require affect regulation, reflective response generation, and management of motivation and emotions (Perone et al., 2018; Prencipe et al., 2011). It should be noted that “hot” and “cool” EF are not distinct processes but rather represent similar basic cognitive functions that fall along a continuum of emotional activation (Perone et al., 2018).

Past research has sought to pinpoint the factors and developmental trajectories underlying hot and cool EF by analyzing differences in outcomes on hot EF tasks and cool EF tasks. Neurophysiological studies suggest that although there is significant overlap in the neural networks involved, there are still difference in the brain areas recruited for hot and cool EF. The dorsal and lateral aspects of the PFC have been shown to be associated with cool EF. For example, during completion of the DCCS (measure of task-switching or shifting), activation in the anterior cingulate cortex (ACC) occurs as soon as participants notice the conflict that is inherent in the rule change. This activation of the ACC catalyzes recruitment of the lateral PFC regions (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Ezekiel, Bosma, & Morton, 2013). Ventro-medial regions of the PFC (including the orbitofrontal cortex), which are connected to the limbic system and are responsible for cognition and emotion integration, have been associated with hot EF (Zelazo & Carlson, 2012; Zelazo & Müller, 2002). Lesion studies have indicated that hot and cool EF may be dissociative, as patients with damage to the orbitofrontal cortex experience impairments on hot EF tasks but still perform well on measures of cool EF (Bechara, Damasio, Tranel, & Anderson, 1998). Even though different areas of the brain may be responsible for hot and cool EF, they do appear to be part of a coordinated system. Situations and contexts that differentially elicit hot or cool EF processes, seem to fall on a continuum that requires increasingly complex and developed abilities (Perone et al., 2018; Prencipe et al., 2011).

Research on developmental trajectories of cool and hot EF from childhood through adolescence supports the continuum viewpoint. While age-related improvements in cool EF are found in childhood (ages 8-13), improvements in hot EF do not occur until adolescence, typically starting around age 14 (Crone & van der Molen, 2004; Hooper, Luciana, Conklin, & Yarger, 2004; Poon, 2018; Prencipe et al., 2011). It should also be noted that adolescents are often not performing at ceiling on measures of hot EF suggesting that it is still developing throughout adolescence (e.g., Prencipe et al., 2011; Hooper et al., 2004). Poon (2018) also argues that while cool EF follows a linear trend across development, hot EF follows a bell-shaped curve (as measured by increases in risk-taking), resulting in a vulnerability to risky-decision making during middle adolescence (ages 14-15). Steinberg (2008) analyzed age-related differences on delayed discounting and future orientation and found that participants who were 16-year-olds and older were more likely than children between the ages of 10-16 to delay an immediate smaller reward for a future larger reward.

Overall, the protracted development of hot EF from childhood through adolescence may denote a critical or "sensitive" period of brain plasticity during middle adolescence (Zelazo & Carlson, 2012). These periods of vulnerability or sensitivity are also opportunities for creating effective and developmentally appropriate cognitive training tools.

Emotional Design and Learning

Typically, tasks involving hot EF, such as the Iowa gambling task, use external rewards to evoke emotions. In real life, a wide variety of experiences can evoke hot EF including dealing with peer pressure, social exclusion, experiencing a delay of gratification, as well as dealing with potential gains or losses. In other words, hot EF is involved in situations that are not only motivationally significant, but also emotionally significant. This means that another option for evoking hot EF in the lab is by using materials that evoke emotions themselves.

An *Emotional Design* approach (Plass et al., 2014; Plass & Kaplan, 2016; Um et al., 2012) is one method of evoking emotions through the design of materials. Designers of digital games have long recognized the importance of emotional responses, and have identify various game features that can be used to induce emotions (Plass et al., 2015). Past research on the effects of visual design (e.g., shapes and colors) has shown that bright, vivid and saturated colors can positively affect emotions and feelings (Gao & Xin, 2006; Tucker, 1987; Valdez & Mehrabian, 1994). Shape of design elements can also induce emotions. Examples include the baby-face bias (Lorenz & Generale, 1960), and anthropomorphism (Hongpaisanwiwat & Lewis, 2003). The baby-face bias refers to the extent to which round shapes, short chins, small noses and large eyes are perceived as baby-like features that induce positive affect over sharped edged shapes (Lorenz & Generale, 1960). Anthropomorphism concerns the tendency for humans to attribute human-like features and characteristics to inanimate objects. For example, animated game characters expressing human-like emotions can serve to elicit and sustain attention and engagement in the learner (Hongpaisanwiwat & Lewis, 2003).

Based on the emotional effects of design features, there has been interest in finding the extent to which specific colors and shapes within multimedia environments can promote learning through elicitation of positive emotions (Mayer & Estrella, 2014; Plass et al., 2014; Um et al., 2012). Um et al. (2012) designed two types of multimedia learning environments on immunization that were identical in terms of their informational content, but differed in their use of shapes and colors. The researchers also examined if internally induced emotions (i.e., emotions evoked through multimedia design), were more sustainable than externally induced emotions (i.e., emotions evoked using a standard mood-induction paradigm). The positive emotional design environment included round shapes and vivid colors, while the neutral emotional design environment included simple square or circle shapes and neutral colors (grays). Um et al. (2012) found that round shapes and vivid colors induced more positive emotions than the neutral shapes and colors. More importantly, learners in the positive emotional design group scored higher on comprehension and transfer measures than did those in the neutral group. Additionally, internally induced emotions were sustained until the end of the learning task, unlike externally induced emotion, which faded before the end of the task. Further, internally induced emotions had a greater effect on comprehension and transfer. These, and subsequent findings (Mayer & Estrella, 2014; Park, Knörzera, Plass, & Brünkena, 2015; Plass et al., 2014), have clearly identified emotional design as an approach that can enhance learning without directly changing the structure or content of the learning environment.

The ability for visual features of game characters to elicit emotions in the learner was further examined by Plass and colleagues (MacNamara et al., 2018; Plass et al., 2018). The researchers were interested in the extent to which four different visual features of game characters (shape, color, expression, and dimensionality) influenced the emotions participants attributed to game characters. In a series of forced-choice trials, participants viewed two images of game characters side by side, that varied in *shape* (round or square), *dimensionality* (2D or 3D with shading), *color* (red or grayscale), and *expression* (happy/sad or neutral), and were required to choose which images made them feel the happiest or saddest. Overall, for both emotions, there was a large effect of expression, and a medium effect of color and shape, with little to no effect of dimensionality. These findings systematically identify features that can be used for emotional design in multimedia for learning or cognitive training, including the design of digital games intended to support the development of EF.

Improving EF through Game-based Training

There has been great interest in identifying ways to systematically trained and improved EF (Best & Miller, 2010; Blair & Razza, 2007; Diamond & Lee, 2011). Interventions based on digital games have been one method to enhance EF skills such as inhibition, working memory, and shifting (Anguera et al., 2013; Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Homer, Plass, et al., 2018; Parong et al., 2017; Strobach, Frensch, & Schubert, 2012). The effectiveness of games for training EF can be attributed to a number of factors, including their ability to preserve engagement and motivation, adapt to the player's current challenge level, and ability to promote distributed practice (Diamond & Lee, 2011; Dye & Bavelier, 2010; Holmes, Gathercole, & Dunning, 2009; Homer, Ober, & Flynn, 2018).

Currently, few if any game-based interventions explicitly target hot EF, although games would seem to be a viable medium for training this ability. Surprisingly, most of the research on game-based trainings of EF has focused on young children, college-aged students and aging adults (Best et al., 2009), with a paucity of research with adolescents, even though this is a period of growth in EF, particularly, as described above, growth in hot EF (Alloway, 2012; Green et al., 2012; Roughan & Hadwin, 2011; Zinke, Einert, Pfennig, & Kliegel, 2012). Additionally, although there is considerable research on the effectiveness of training working memory, there is much less work on training of other EF skills, such as shifting, even though the importance of shifting for outcomes such as academic success has been well established (Homer & Plass, 2014; Yeniad, Malda, Mesman, van Ijzendoorn, & Pieper, 2013). As stated above, shifting, or cognitive flexibility, requires the ability to switch from adhering to one rule to another with minimal perseveration and increasing flexibility. It emerges in early childhood and continues to develop into adolescence. Deficits in shifting have been associated with a number of neuro-cognitive disorders, including autism (e.g., Ozonoff, Pennington, & Rogers, 1991), and ADHD (e.g., Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

There have been a few successful efforts to train shifting in adolescents. For example, Homer, Plass, et al., (2018) asked high school students to play a digital game designed to improve the EF subskill of switching at least once a week over the course of 6 weeks. High school students who played the game demonstrated significant pre- to post gains in shifting (as measured by the DCCS), as well as near transfer to inhibition (as measured by the Flanker task). Similarly, Parong et al. (2017), established the validity of an adaptive game-based training targeting shifting called *All You Can E.T.* (AYCET). The researchers found that late-adolescent college students who completed at least 2 hours of game-play over multiple sessions displayed greater improvements on two measures of cognitive flexibility or shifting (i.e., the DCCS and letters and numbers task) than did active controls who played a word search game. A second experiment confirmed these results by comparing those in the experimental group to an inactive control group. These studies provide evidence that it is possible to improve the EF subskill of shifting through a digital game-based intervention, particularly with a game that was developed with the explicit intention of training EF.

Current Study

The current study investigates how the design of a game for training EF in adolescents (aged 12-16) can be enhanced by considering the neurophysiological and cognitive changes related to EF occurring during this developmental period. Specifically, an *emotional design* approach (Plass et al., 2014) was used to make a “hot” and “cool” version of *All You Can E.T.* (AYCET; Parong et al., 2017), a digital game designed to train the EF subskill of shifting. The hot version of AYCET was created by altering attributes of the game characters by using bright colors and emotional expressions, and a cool version was created by using characters with more emotional neutral attributes, including gray-scale coloring and neutral expressions. Given that hot EF undergoes increased development beginning at mid-adolescence (Principe et al., 2011; Zelazo & Carlson, 2012), it was hypothesized that the hot version of the game would be particularly beneficial for adolescents starting around age 15. Finally, for the purpose of the current research, we only examined the effects of training over a 20 minutes period. Although sustained EF improvements most likely require a more prolonged intervention, some of our prior research has shown that small, but significant gains in EF can be observed even after a brief intervention (e.g., Homer, Ober, Rose, et al., 2018).

For the current study, we posed four related research questions:

Research Question 1: Will there be significant changes in EF after playing AYCET?

a) Following 20-minutes of gameplay of AYCET, will there be significant changes in participants’ EF subskill of shifting as indicted by posttest scores on the DCCS?

b) Will any pre- to posttest differences in shifting vary between the two conditions?

We hypothesize a) significant gains in shifting from pretest to posttest, and b) significantly greater gains in the hot condition.

Research Question 2: Will age and AYCET condition interact to affect adolescents' improvements of EF?

Given that hot EF develops later in adolescence, we hypothesize that the benefits of the hot condition of AYCET would be greater for the older adolescents.

Research Question 3: Do differences in game-based performance predict posttest scores in the EF subskill of shifting, as indicted the DCCS?

We hypothesize that better game metrics will predict better posttest scores in measures of EF.

Research Question 4: Are there significant differences between the two AYCET conditions in game-based performance metrics (i.e., measures of speed and accuracy)?

We hypothesize that participants in the hot condition of AYCET will demonstrate significantly better speed and accuracy during gameplay.

Methods

Participants

Participants (N = 233) were 12- to 16-year-old adolescents (M = 14.03, SD = 1.33) from public schools in New York City. Approximately 44% of the students identified as female, 56% identified as male, with one of the adolescents declining to self-identify gender. Of those participants who indicated their ethnicity, the majority self-identified as Hispanic/Latino (90.1%), with the remainder self-identifying as Asian or Pacific Islander (4.3%), white/Caucasian (2.8%), and African American (2.8%). As an indication of SES, participants were asked about their mother's highest level of education, the following was reported: 5% had completed up until at least 8th grade but had not completed high school; 14% had some high school education but had not completed a degree; 16% had completed high school; 17% had some college; 17% had a college degree; and 6% had some graduate school experience. The remainder of participants either did not respond or indicated they did not know their mother's highest level of education (15.0%).

Materials

All You Can E.T. (AYCET).

All You Can E.T. (AYCET) is an adaptive digital-game designed to train the EF subskill of shifting. AYCET was created by game developers and researchers at the CREATE lab at NYU. As mentioned above, interventions using earlier versions of this game have been shown to significantly improve adolescences' EF subskill of shifting (e.g., Homer, Plass, et al., 2018; Parong et al., 2017), with some increase (as indicated by pre- to posttest gains in scores on the DCCS) found even after just 20 minutes of gameplay (e.g., Homer, Ober, Rose, et al., 2018).

The objective of AYCET is to give aliens the appropriate food or drink. The game is governed by rules, with rule changes occurring within each level and between levels. During AYCET, the player is required to give different types of aliens (e.g., one-eye vs. two-eye; red vs. blue) either food or drink. Correct responses depend on the relevant rules that are presented to the player before or during each level. For example, a rule may require the player to give food to two-eyed aliens and a drink to one-eyed aliens. A rule change would then let the player know that they need to now allocate a food to one-eyed aliens and drink to two-eyed aliens. The game interface notifies players of rules and rule changes. As levels increase, the rules and rule-changes become more complex (e.g., one-eyed red aliens and two-eyed blue aliens need food; two-eyed-red aliens and one-eyed blue aliens need drink). The complete game has a total of 16 levels, but with only 20 minutes of gameplay, participants in the current study would not have enough time to complete all levels. AYCET is adaptive in that it changes the speed of oncoming aliens based on the player's performance; speeding up if the player is accurate and responding quickly, slowing down if the player is making errors or is taking a long time to respond. Due to its adaptive nature, players may experience different amounts game levels and rule changes. Game play lasted for 20 minutes.

For the current study, two versions of AYCET were created: a "hot" version and a "cool" version. The hot version was designed to more induce greater emotions in players. (See Figure 1.) This version featured round-shaped aliens that were vividly colored (i.e., red and blue). When a player makes a correct hit (e.g., when they correctly give blue one-eyed aliens a drink) the alien goes from expressing a neutral emotion to a happy emotion (i.e., smiles). When the player makes an incorrect hit (e.g., when they incorrectly give blue one-eyed aliens food) the alien goes from showing a neutral expression to a sad frowning expression.

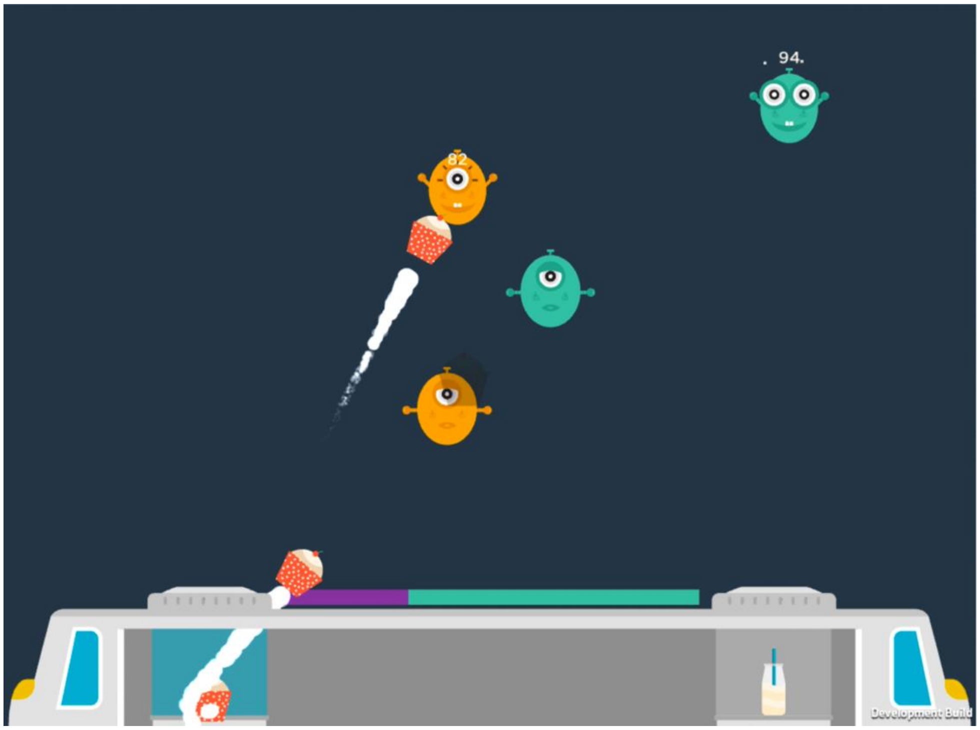

Figure 1. Screen capture of the hot EF condition showing alien's emotionally expressive features and vivid color palette.

The cool version was identical to the hot version except the Aliens were designed to not induce as strong of an emotional response in players. (See Figure 2.) This version featured square-shaped aliens that were colored using a grey-scale pallet. Furthermore, the aliens did not express joy or sadness when fed correctly or incorrect, although feedback was given to the players.

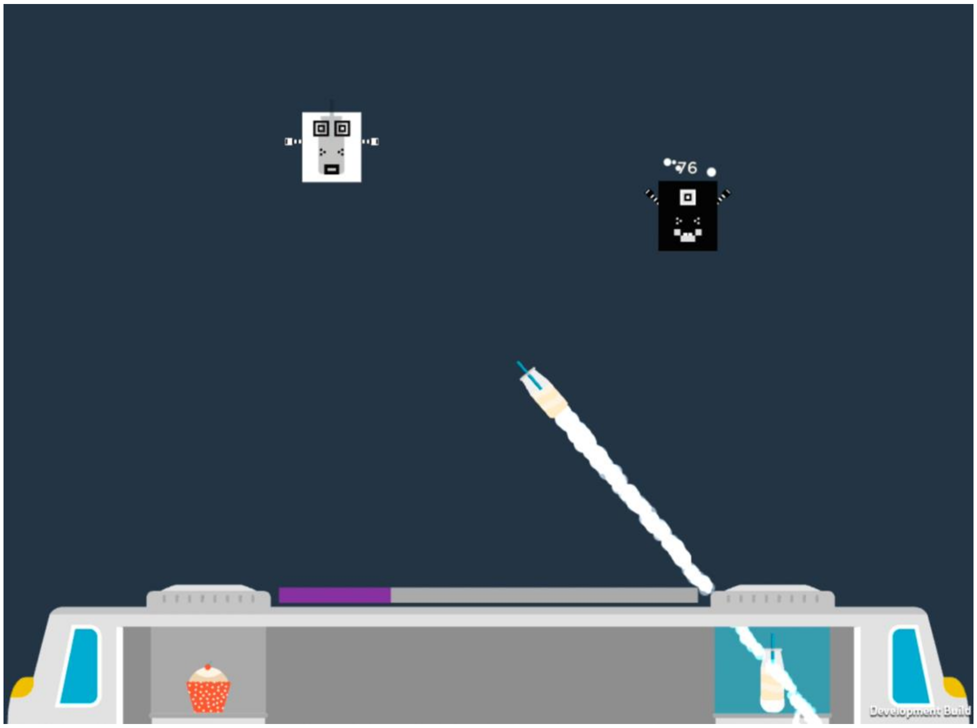

Figure 2. Screen capture of the cool EF condition showing alien's neutral emotional expressive features and a grayscale color pallet.

Game Log Data.

AYCET game log data was recorded through DREAM integrated research platform while participants played one of the two versions of the game. Metrics from the log data were used as indicators of performance. Specifically, as a measure of accuracy, the proportion of targets correctly hit over the total number of presented targets was calculated for each level. As a measure of speed, the average reaction time for targets correctly hit for each level was recorded.

Demographic Survey & Postgame Questionnaire.

Participants received a brief demographic questionnaire. This questionnaire asked about gender, age, race, and parental education history. After completing the game, participants were given a brief, 3-question survey about their feelings for the aliens in the game. Participants were asked to rate on a 7-point Likert scale the extent to which: 1) they were happy when they helped the aliens; 2) they were sad when they didn't help the aliens; and 3) they cared about what happened to the aliens. A total "Emotional Engagement" score was then calculated by summing scores on the three questions.

Dimensional Change Card Sort Task (DCCS).

Designed by Zelazo and colleagues (Zelazo, 2006; Zelazo et al., 2013), the DCCS is used to measure cognitive flexibility or task shifting. Although the DCCS has been used most commonly with children, the version used in the current study, which was based on the computerized version of the DCCS included in the NIH Toolbox Cognition Battery (Zelazo et al., 2013), has been validated for ages 3-85. This version of the DCCS has strong test-retest reliability (ICC=.92) and convergent and discriminant validity (Zelazo et al., 2013).

The computerized version of the DCCS consists of practice and test blocks. During the practice blocks, participants are shown two target stimuli on either side of the screen and asked to match a stimulus presented in the middle of the screen to one of the two target stimuli depending on a rule. For practice and test blocks, the rule appears on the screen between each trial. For the practice block, participants are provided with feedback concerning their correct or incorrect responses. In the practice block, participants were instructed to match bivalent test stimuli to target stimuli (e.g. white rabbit and a green boat) according to the rule (i.e., shape or color). In the test blocks, participants were presented with pictures that varied across two dimensions: 1) shape (e.g., baseball versus sailboat), and 2) color (e.g., blue versus yellow). Performance was measured by a combination of speed and the number of accurate trials.

Procedure

Participants were recruited through partnerships with schools in New York City. Parental consent was obtained before the students participated in the study. Testing took place in classgroups at a university-based research lab. When arriving at the lab, the students were individually randomly assigned study ID numbers, which had previously been associated with access codes corresponding to either the hot or cool version of AYCET. In smaller groups, the participants would sit down at the lab computers and enter their ID and access codes into the appropriate field of the *Digital Reference, Experiment, and Assessment Manager* (DREAM; CREATE, 2016), a web-based platform that enables researchers to upload study contents and allows participants to access contents using access codes. In DREAM, participants assented to participant in the study, and then completed the following tasks in sequential order: DCCS pretest, 20 minutes of AYCET Hot or Cool Version, Emotional Game Characteristics Questionnaire, DCCS posttest and Demographics and GamePlay Questionnaire. Game log data was continuously collected while the player completed AYCET. Research assistants were available during the study to answer questions but provided minimal assistance to participants. After completing the session, participants were debriefed in a group session.

Results

Data was collected through the DREAM system, an integrated research and digital media delivery platform. Performance on the DCCS pretest score was examined to identify outliers following Tukey's method (Tukey, 1977), with the modification that instead of removing outliers beyond 1.5 IQR, we removed values beyond 3 IQR from the first and third quartiles. In data that involves reaction times and is derived from a developmental sample, greater variability is to be expected, and so this decision made to allow for the greater variability inherent in the sample. In total, 3 participants were removed from the sample, all of whom had pretest scores that were significantly below the overall average. This left a final sample size of 233, with 126 who had been randomly assigned to the cool condition of AYCET and 107 who had been assigned to the hot condition.

Initial analyses examined the *Emotional Engagement* score, which was calculate by summing responses to the three post-game questions about how much participants cared about the aliens in AYCET. A significant difference was found between the emotional engagement score for the two conditions, t (230) = 2.34, p = .02, D = .30, with participants in the emotionally hot condition (M = 10.2, SD = 2.8) indicating more emotional investment in the aliens than participants in the cool condition (M = 9.3, SD = 3.2). However, participants' emotional engagement score was not related to posttest DCCS scores, r = .07, p = .28, and so the variable was not included in subsequent analyses. Similarly, possible effects of gender on DCCS posttest scores was examined, and no significant gender differences were found, t (230) = .33, p = .74. Therefore, gender also was not included as a factor in the subsequent analyses.

Effects of Condition and Prior-EF on Posttest DCCS Scores

To determine if there was an overall gain in shifting as measured by changes pre- to posttest on the DCCS, a paired sample t-test was conducted. Results indicated that there was a significant difference, t (232) = 4.10, p < 0.001, d = 0.27, with average DCCS posttest score (M = 7.25, SD = 1.38) being significantly higher than average DCCS pretest score (M = 6.80; SD = 1.70). Further analyses were then conducted to examine the effects of condition and age on posttest DCCS scores.

To examine the effects of age and condition on shifting, an ANCOVA was conducted with DCCS posttest score as the dependent variable, condition (hot vs. cool) as an independent factor, and DCCS pretest score and age as covariates. Results indicated a significant main effect of condition, F(1, 225) = 4.91, p = .03, partial eta squared = .02. Examination of the adjusted marginal means indicated that the hot condition had significantly greater average posttest scores (*M* = 7.33, *SE* = 1.22) than did the cool condition (*M* = 7.17, *SE* = .11). There was also a significant main effect of age, $F(1, 225) = 4.15$, $p = .04$, partial eta squared = .02. The main effects were mitigated by a significant age by condition interaction, $F(1, 225) = 4.96$, $p = .03$, partial eta squared = .02, indicating that the effects of condition were different for different aged participants. To further examine the interaction between condition and age, a DCCS change score was created by calculating the difference between posttest and pretest scores on the DCCS. As illustrated in Figure 3, for the youngest participants difference in pre- to posttest change in DCCS was about the same for both the hot and cool conditions. In contrast, the older participants showed significantly greater gains in the hot condition than in the cool condition.

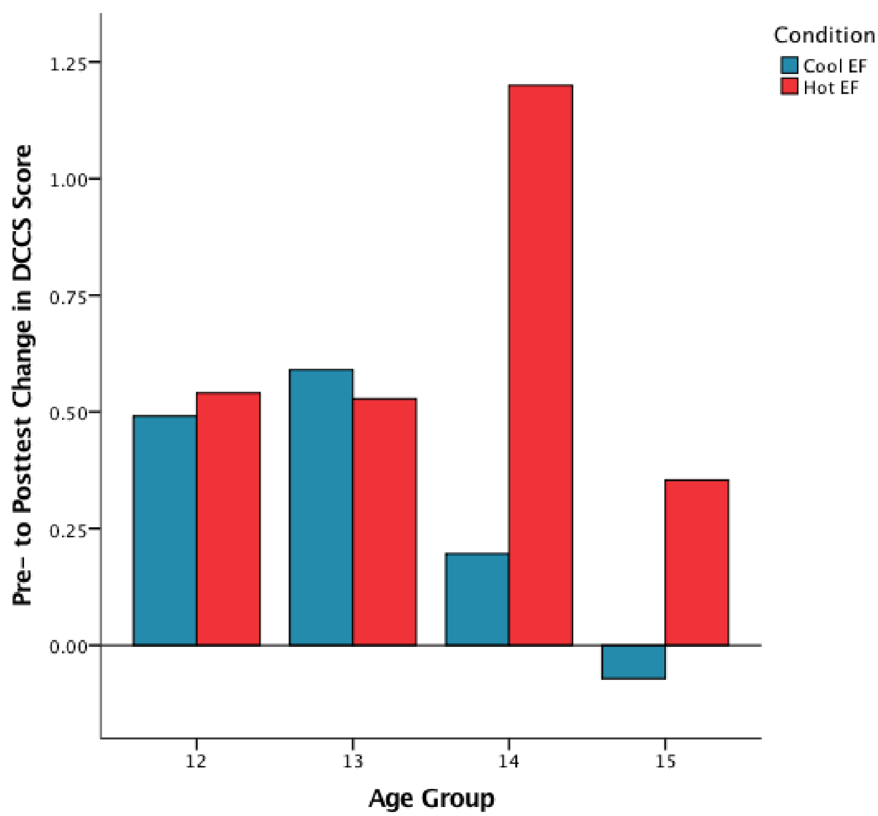

Figure 3. Pre- to Posttest Gains in Shifting (DCCS) by Age Group for Hot and Cool AYCET Conditions

A significant condition by pre-DCCS score interaction was also found, $F(1, 225) = 4.11$, $p = .04$, partial eta squared = .02, indicating that the effects of condition were different for participants with different initial pre-DCCS scores. As seen in Figure 4, there was little difference between conditions in posttest scores for participants with lower initial DCCS scores. In contrast, the hot condition had slightly greater posttest DCCS scores compared to the cool condition for participants with higher initial DCCS scores. Finally, a significant three-way interaction was found between condition, age and pre-DCCS, $F(1, 225) = 4.09$, $p = .04$, partial eta squared = .02, indicating that the age by condition interaction was affected by participants pre-DCCS score.

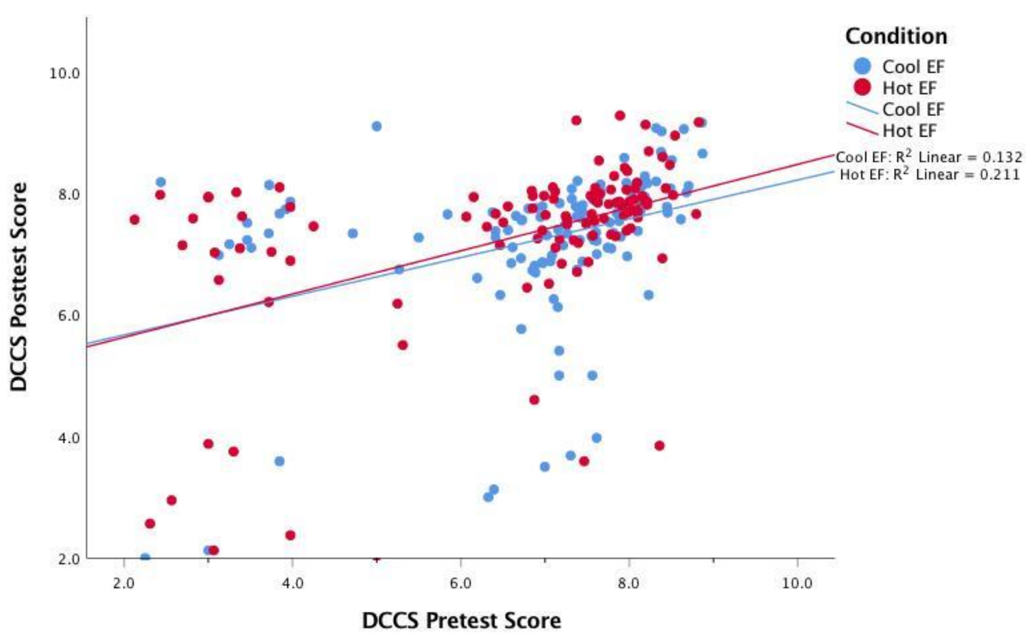

Figure 4. Posttest DCCS Scores in Relation to Pretest DCCS Scores for Hot and Cool AYCET Conditions

Analyses of Game Data

Computer log data of the player's interactions with the program while playing the game were recorded and analyzed. The computer log data was used to compare performance within the context of the game between the two conditions. Specific metrics included an accuracy measure of number of correct hits (i.e., number of "aliens saved"), and a speed measure of average reaction time. Independent t-tests conducted to determine if there were differences between the hot and cool conditions on the game metrics indicated no significant differences between conditions for the number of correct hits, $t(231) = 1.18$, $p = .24$, or average reaction time, $t(231) = 1.57$, $p = .23$.

Relation of Game Log Data to Posttest DCCS Scores

To determine if in-game performance was related to posttest score of shifting, correlations between the game performance metrics and DCCS posttest score calculated. Because there were no significant differences between conditions in the in-game metrics, the two conditions were considered together. Results from the analyses indicated that the correlation between the correct hits and the DCCS posttest score was significant, $r = 0.24$, $p < 0.001$. The correlation between average reaction time and DCCS posttest scores was also significant, $r = -0.21$, $p = 0.001$.

It may be that higher preexisting levels of EF allow participants to perform well on the AYCET game and also predict higher scores on the DCCS posttest. To account for this, partial correlations were conducted. Results from the partial correlations indicated that controlling for the effects of pretest DCCS, there is still a significant relation between the number of correct in-game hits and the DCCS posttest, $r = 0.20$, $p = 0.002$. The correlation between average reaction time and DCCS posttest scores when controlling for pretest DCCS score was also significant, r = -0.13, p = 0.049.

Discussion

The goal of the current study was to investigate how developmental theory can inform the design of digital tools for learning and cognitive skills development. We examined implications of what is known about the neurophysiological and cognitive changes related to EF development during early to mid-adolescence, particularly developments in hot EF, for the design of a digital game to enhance the EF subskill of shifting. To do this, we used an emotional design approach (Plass et al., 2018; Um et al., 2012) to create two version of the EF training game, AYCET: one that was emotionally “hot”, and one that was emotionally “cool”. Overall, participants in both conditions demonstrated small, but significant improvements in the EF subskill of shifting (as measured by changes in the DCCS pre- to post-intervention), but the emotionally hot version of the game yielded significantly greater gains in EF. This was particularly true for the older adolescents in our study (ages 14 to 16 years), with little difference between the two conditions found for the younger adolescents (ages 12 to 13 years). Additionally, the hot condition was more effective for the adolescents with higher initial levels of EF, although this was a relatively small effect. Finally, a three-way effect between condition, age and prior EF suggests that both developmental and individual factors play a role in determining the most effective approach for training adolescents’ EF skills via digital games.

These findings support our hypothesis that there would be significant gains in participants EF subskill of shifting, even after just 20-minutes of gameplay. They also supported our hypothesis that improvements in shifting would be greater for participants in the hot EF training group, particularly for the older adolescents in the study. These results are among the first to establish a connection between emotional design of a game and improvements of cognitive skills. It should be noted that in general, the greatest improvements occur with the younger adolescents and the participants who had lower initial EF abilities. This is consistent with other studies on EF training, which have generally tended to be the most effective for individuals with the lowest EF at the beginning of the training (e.g., Homer, Ober, Rose, et al., 2018; Karbach & Kray, 2009; Holmes et al., 2009).

Another set of questions involved the in-game metrics of accuracy (i.e., number of correct hits/aliens saved) and speed (i.e., average reaction time). As hypothesized, after accounting for pre-test DCCS score, both in-game metrics predicted posttest DCCS scores. This is consistent with the claim that the in-game activities of AYCET are supporting the development of the EF subskill of shifting. This approach of matching specific in-game activities to learning or developmental outcomes represents an effective way of validating the efficacy of specific game-based interventions. While randomized controlled trials remain the "gold standard" for determining whether or not an intervention is effective, game log data can help identify the specific in-game activities that are responsible for the desired outcomes, which can then inform the design of more effective games for learning. Contrary to our hypothesis, there were no significant differences between conditions on either of the in-game measures. The role of emotions in games for learning is often seen as solely enhancing engagement and motivation (Jabbar & Felicia, 2015). However, the finding of no between-group differences in the in-game metrics suggests that, in the current study, participants in the hot condition were not just more motivated and trying harder, as this would have resulted in better performance on the game.

So, what exactly accounts for the effects of the hot condition of AYCET? The most likely factor is that increased emotional activation during play of the game is making the difference. Participants in the hot condition did report significantly more emotional engagement with the game characters in AYCET, even though the effect was modest and was not significantly related to pre- to posttest gains in shifting. Additional research is needed to further explore this hypothesis, ideally collecting direct physiological measures during game-play to see if emotion response is predicting gains in EF. If increased engagement of emotion is making a difference, this would be consistent with the claim that tapping into adolescences development of hot EF can enhance the effects of interventions to improve EF. Perone et al. (2018) argue that the development of connections between the fronto-parietal and fronto-limbic networks during adolescence is involved in the development of hot EF. Although more data is needed to establish the neurophysiological underpinnings of hot EF, the timing does coincide with behavioral indications of hot EF, which show marked improvements in mid-adolescence, by 14 years of age (Prencipe et al., 2011). The developmental timing is consistent with the findings of the current study, in which the hot condition resulted in improve EF gains starting around 14 years of age. Interestingly, the effects seem to diminish by 15-years-old, although the efficacy of the emotional design approach for older adolescence should be investigated in future research.

The findings from the current study contribute to earlier work examining the effects of emotional design on performance (Plass et al., 2014; Um et al., 2011), extending beyond this earlier work by examining the effects of emotional design in a game for improving cognitive skills in adolescents. Although adolescence can be a difficult developmental period to study (Davidson et al., 2006; Leshem, 2016), the current findings indicate a promising trend for creating more efficacious design features that may harness some of aspects of neurocognitive changes that occur during this important period of development.

Limitations and Future Directions

There are some limitations of the current study that should be addressed in future work. First, although significant pre- to posttest gains in shifting were found, given the brevity of the current intervention (i.e., 20 minutes), the permanence of the gains is not clear. The goal of the current study was to examine the viability of using an emotional design approach for game-based EF interventions for adolescents. Given the promising results of the current study, next steps should include a longer intervention in a study that includes a control group in order to provide clearer evidence of the efficacy of the emotional design approach with digital games to make lasting improvements in adolescents' EF. Prior research has found significant gains in EF with adolescents using versions of AYCET (e.g., Homer, Plass, at al., 2018; Parong et al., 2017), but to see if the hot version of the game is having a significant, lasting effect, future studies should compare the cool and hot EF versions over a longer training regimen.

Secondly, measures of hot EF were not included in the current study. The study focused on the EF subskill of shifting, asking if a version of AYCET that was more emotionally engaging could enhance training of shifting in adolescence. However, additional work should determine both if adolescences' prior level of hot EF influences the effects of the emotional design of the game, and if adolescents experienced improvements on hot EF as a result of playing AYCET. It seems possible that for the older adolescents, there may be greater gains in hot EF given that this is an essential development at that age. Furthermore, gains in hot EF may contribute adolescents' ability to regulate emotions and may explain variability in emotional regulation (Woltering, Lishak, Hodgson, Granic, & Zelazo, 2016). Therefore, future work should examine not only gains in measures of cool and hot EF, but also possible benefits for crucial related skills, such as emotional regulations, that develop during adolescence.

Related to this, more fundamental work is needed to understand further the relation between hot and cool EF, and how the nature of this interaction changes over the course of children and adolescent development. Neurophysiological research is needed to examine the specific systems involved. For example, did older adolescent in the current study recruit more from regions in the PFC along with regions associated with reflective processing? Future studies examining the neural underpinnings associated with cognitive training success in an emotional design environment and how these change across development are warranted (Perone et al., 2018).

Another issue is that the cool version of AYCET was not actually all that “cool” and the “hot” version was not all that “hot”. A number of features in the cool version included emotionally relevant stimuli. For example, when a player made a correct hit in the cool version, the alien’s expression changed from neutral to a smile. The time pressure and points awarded for saving aliens was the same in both conditions, and very likely evoked some emotions. A truly neutral or cool version would not have included any type of emotional valence. With that said, the change in expression in the cool version was necessary as it served as feedback for the learner – and helped make the game enjoyable. Similarly, the hot version could be even “hotter”. For example, the game could have had even more emotionally salient stimuli or reward mechanisms (e.g., by having and engaging narrative or greater rewards and risks). Other game features, such as sounds and musical score, are known to affect player’s emotional response, and could be used to make the game even “hotter”. In ongoing research, we are also examining the use of virtual reality as a way of creating a game that is highly emotionally engaging – although this brings up the possibility that there may be point at which the emotional engagement of the game could be too great, and actually have a negative effect on learning outcomes. It seems likely that an “emotional sweet spot” for these types of interventions may exist, that will depend not only on the specific content of the games, but also on the developmental level of the participants as well as individual variability in specific skills and abilities (e.g., level of hot and cool EF, emotional regulation, etc.).

This relates to another area for future work, which involves adaptivity and personalization of games for learning and cognitive training. The most common way of adapting is to vary the difficulty of a game. Constantly challenge the learner has been shown to be an effective way of improving cognitive skills (Diamond & Lee, 2011). Adaptive algorithms, which monitor players' performance and change the difficulty of the game accordingly, have been proven to be effect ways to keep players challenged at just above their current level of performance (Ericsson, 2006; Klingberg, 2010; von Bastian & Eschen, 2016). In the current study, both version of AYCET incorporated an adaptive algorithm that adapted challenge level based on in-game performance (i.e., speeding up delivery of aliens if the player was doing well, slowing it down if they were having problems). The results of this study suggest that, in addition of performance, developmental stage and individual variation in emotional response may be other factors that could inform the adaptive design of games for learning.

Conclusion

In the current study, an *emotional design* approach was used to activate hot EF in adolescents playing AYCET, a digital game designed to train the EF subskill of shifting. In general, the hot condition of the game, which was designed to be more emotionally activating, was more effective than the cool condition, particularly for the older adolescents and for adolescents with higher initial levels of EF. Overall, these results provide evidence for effective integration of emotional design into interventions for cognitive interventions. Furthermore, the results provide an example of how developmental theory can inform the design of effective games for learning and cognitive skills improvement. The results of the current study also have implications for our understanding of the developmental of EF, specifically supporting the notion that hot and cool EF are not separate, but rather are part of an integrated system, with developments in hot EF lagging behind cool EF (Perone et al., 2018; Prencipe et al., 2011). Although additional research is needed to understand the developmental trajectory and neurophysiological underpinnings of hot and cool EF, as well as to explore the best ways to use emotional design to active hot EF in adolescents, the current study begins to provide some insight for understanding of both theoretical and applied issues involved in EF.

Acknowledgement

This work was supported in part by a research grant from the Institute of Educational Sciences, US Department of Education (Grant #R305A150417). The opinions expressed are those of the authors and do not represent the views of the Institute or the U.S. Department of Education.

References

Alloway, T. (2012). Can interactive working memory training improve learning? *Journal of Interactive Learning Research*, *23*(3), 197–207.

Anguera, J. a, Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., … Gazzaley, A. (2013). Video game training enhances cognitive control in older adults. *Nature*, *501*(7465), 97–101. https://doi.org/10.1038/nature12486.Video https://doi.org/10.1371/journal.pone.0142169

Barnea-Goraly, N., Menon, V., Eckert, M., Tamm, L., Bammer, R., Karchemskiy, A., … Reiss, A. L. (2005). White matter development during childhood and adolescence: A cross-sectional diffusion tensor imaging study. *Cerebral Cortex*, *15*, 1848–1854. https://doi.org/10.1093/cercor/bhi062

Bechara, A. (2004). The role of emotion in decision-making: Evidence from neurological patients with orbitofrontal damage. *Brain and Cognition*, *55*(1), 30–40. https://doi.org/10.1016/j.bandc.2003.04.001

Bechara, A., Damasio, H., Tranel, D., & Anderson, S. W. (1998). Dissociation of working memory from decision making within the human prefrontal cortex. *The Journal of Neuroscience*, *18*(1), 428–437. https://doi.org/10.1523/JNEUROSCI.18-01-00428.1998

Best, J. R., & Miller, P. (2010). A developmental perspective on executive function. *Child Development*, *81*(6), 1641–1660. https://doi.org/10.1111/j.1467-8624.2010.01499.x.A

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review*, *29*(3), 180–200. https://doi.org/10.1016/j.dr.2009.05.002

Blair, C., Granger, D. A., Willoughby, M., Mills-Koonce, R., Cox, M., Greenberg, M. T., … FLP Investigators. (2011). Salivary cortisol mediates effects of poverty and parenting on executive functions in early childhood. *Child Development*, *82*(6), 1970–1984. https://doi.org/10.1111/j.1467-8624.2011.01643.x.Salivary

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development*, *78*(2), 647–663. https://doi.org/10.1111/j.1467-8624.2007.01019.x

Blair, C., & Razza, R. P. (2008). Biological processes in prevention and intervention: The promotion of self-regulation as a means of preventing school failure. *Development and Psychopathology*, *20*(3), 899–911. https://doi.org/10.1017/S0954579408000436

Blakemore, S., & Choudhury, S. (2006). Development of the adolescent brain: Implications for executive function and social cognition. *Journal of Child Psychology and Psychiatry*, *47*(3), 296–312. https://doi.org/10.1111/j.1469-7610.2006.01611.x

Blakemore, S., & Robbins, T. W. (2012). Decision-making in the adolescent brain. *Nature Neuroscience*, *15*(9), 1184–1191. https://doi.org/10.1038/nn.3177

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychologica*, *129*(3), 387–398. https://doi.org/10.1016/j.actpsy.2008.09.005

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. https://doi.org/10.1037//0033-295X.I08.3.624

Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology*, *28*(2), 595–616. https://doi.org/10.1207/s15326942dn2802_3

CREATE. (2016). DREAM. Retrieved from create.nyu.edu/dream

Crone, E. A., & van der Molen, M. (2004). Developmental changes in real life decision making: Performance on a gambling task previously shown to depend on the ventromedial prefrontal cortex. *Developmental Neuropsychology*, *25*(3), 251–279. https://doi.org/10.1207/s15326942dn2503

Dahl, R. E. (2004). Adolescent brain development: A period of vulnerabilities and opportunities. Keynote address. *Annals of the New York Academy of Sciences*, *1021*(1), 1–22. https://doi.org/10.1196/annuals.1308.001

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4-12 years old. *Science*, *333*(6045), 959–964. https://doi.org/10.1126/science.1204529.

Dye, M. W., & Bavelier, D. (2010). Differential development of visual attention skills in school-age children. *Vision Research*, *50*(4), 452–459. https://doi.org/10.1016/j.visres.2009.10.010

Ericsson, K. A. (2006). The influence of experience and deliberate practice on the development of superior expert performance. *The Cambridge handbook of expertise and expert performance*, *38*, 685-705.

Ezekiel, F., Bosma, R., & Morton, J. B. (2013). Dimensional Change Card Sort performance associated with age-related differences in functional connectivity of lateral prefrontal cortex. *Developmental Cognitive Neuroscience, 5*, 40–50. https://doi.org/10.1016/j.dcn.2012.12.001

Finn, A. S., Minas, J. E., Leonard, J. A., Mackey, A. P., Salvatore, J., Goetz, C., … Gabrieli, J. D. E. (2016). Functional brain organization of working memory in adolescents varies in relation to family income and academic achievement. *Developmental Science*, 1–15. https://doi.org/10.1111/desc.12450

Gao, X., & Xin, J. H. (2006). Investigation of human's emotional responses on colors. *Color Research & Application*, *31*(5), 411–417. https://doi.org/10.1002/col.20246

Green, C. T., Long, D. L., Green, D., Iosif, A., Dixon, J. F., Miller, M. R., … Schweitzer, J. B. (2012). Will working memory training generalize to improve off-task behavior in children with attention-deficit/hyperactivity disorder? *Neurotherapeutics*, *9*(3), 639–648. https://doi.org/10.1007/s13311-012-0124-y

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, *12*(4), F9–F15. https://doi.org/10.1111/j.1467-7687.2009.00848.x

Homer, B. D., Ober, T. M., & Flynn, R. M. (2018). Children and adolescents' development of executive functions in digital contexts. In *Proceedings of the Technology, Mind, and Society* (p. 17). ACM.

Homer, B.D., Ober, T.M., Rose, M.C., MacNamara, A., Mayer, R. & Plass, J.L. (2018). *Speed Versus Accuracy: Implications of Adolescents' Neurocognitive Developments in a Digital Game to Train Executive Functions*. Manuscript under review.

Homer, B. D., & Plass, J. L. (2014). Level of interactivity and executive functions as predictors of learning in computer-based chemistry simulations. *Computers in Human Behavior*, *36*, 365–375. https://doi.org/10.1016/j.chb.2014.03.041

Homer, B. D., Plass, J. L., Raffaele, C., Ober, T. M., & Ali, A. (2018). Improving high school students' executive functions through digital game play. *Computers and Education*, *117*, 50–58. https://doi.org/10.1016/j.compedu.2017.09.011

Hongpaisanwiwat, C., & Lewis, M. (2003). Attentional effect of animated character. In *Proceedings of the human-computer interaction.* (pp. 423–430). Zurich, Switzerland: IOS Press.

Hongwanishkul, D., Happaney, K. R., Lee, W. S. C., & Zelazo, P. D. (2005). Assessment of hot and cool executive function in young children: age-related changes and individual differences. *Developmental Neuropsychology*, *28*(2), 617–644. https://doi.org/10.1207/s15326942dn2802_4

Hooper, C. J., Luciana, M., Conklin, H. M., & Yarger, R. S. (2004). Adolescents' performance on the Iowa Gambling Task: Implications for the development of decision making and ventromedial prefrontal cortex. *Developmental Psychology*, *40*(6), 1148–1158. https://doi.org/10.1037/0012-1649.40.6.1148

Hughes, C. (2011). Changes and challenges in 20 years of research into the development of executive functions. *Infant and Child Development*, *20*(3), 251–271. https://doi.org/10.1002/icd.736

Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, *44*(11), 2017–2036. https://doi.org/10.1016/j.neuropsychologia.2006.01.010

Huizinga, M., & van der Molen, M. W. (2007). Age-group differences in set-switching and set-maintenance on the wisconsin card sorting task. *Developmental Neuropsychology*, *31*(2), 193–215. https://doi.org/10.1080/87565640701190817

Isquith, P. K., Crawford, J. S., Espy, K. A., & Giola, G. A. (2005). Assessment of executive function in preschool-aged children. *Mental retardation and developmental disabilities research reviews*, *11*(3), 209–215. https://doi.org/10.1002/mrdd.20075.

Jabbar, A.I.A., & Felicia, P. (2015). Gameplay engagement and learning in game-based learning: A systematic review. *Review of Educational Research*, *85*(4), 740-779.

Jones, L. B., Rothbart, M. K., & Posner, M. I. (2003). Development of executive attention in preschool children. *Developmental Science*, *6*(5), 498–504. https://doi.org/10.1111/1467-7687.00307

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review*, *9*(4), 637–671. https://doi.org/10.1001/archpsyc.64.3.327

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental science*, *12*(6), 978-990

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in cognitive sciences*, *14*(7), 317-324.

Leshem, R. (2016). Brain development, impulsivity, risky decision making, and cognitive control: Integrating cognitive and socioemotional processes during adolescence-An introduction to the special issue. *Developmental Neuropsychology*, *41*, 1–5. https://doi.org/10.1080/87565641.2016.1187033

Lorenz, K., & Generale, S. (1960). Ganzheit und Teil in der tierischen und menschilichen Germeinschaft [Wholeness and part in animal and human community]. *Part and Parcel in Animal and Human Societies*, *3*, 9.

Luna, B., & Sweeney, J. A. (2004). The emergence of collaborative brain function: FMRI studies of the development of response inhibition. *Annals of the New York Academy of Sciences*, *1021*(1), 296–309. https://doi.org/10.1196/annals.1308.035

MacNamara, A., Ober, T. M., Rose, M. C., Olsen, A., Homer, B. D., & Plass, J. L. (2018). Emotional design of games for learning: Effects of game character shape, color, expression, and dimensionality. In *AERA 2018 Meeting*. New York, NY.

Mayer, R. E. (2014). *Computer games for learning: An evidence-based approach* (1st ed.). Cambridge, MA: MIT Press.

Mayer, R. E., & Estrella, G. (2014). Benefits of emotional design in multimedia instruction. *Learning and Instruction*, *33*, 12–18. https://doi.org/10.1016/j.learninstruc.2014.02.004

Miller, M., & Hinshaw, S. P. (2010). Does childhood executive function predict adolescent functional outcomes in girls with ADHD?. *Journal of abnormal child psychology*, *38*(3), 315-326.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, a H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Noble, K. G., McCandliss, B. D., & Farah, M. J. (2007). Socioeconomic gradients predict individual differences in neurocognitive abilities. *Developmental Science*, *10*(4), 464–480. https://doi.org/10.1111/j.1467-7687.2007.00600.x

Ortner, C. N. M., Kilner, S. J., & Zelazo, P. D. (2007). Mindfulness meditation and reduced emotional interference on a cognitive task. *Motiv Emot*, *31*, 271–283. https://doi.org/10.1007/s11031-007-9076-7

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology and Psychiatry*, *32*(7), 1081–1105. https://doi.org/10.1111/j.1469-7610.1991.tb00351.x

Park, B., Knörzera, L., Plass, J. L., & Brünkena, R. (2015). Emotional design and positive emotions in multimedia learning: An eyetracking study on the use of anthropomorphisms. *Computers & Education*, *86*, 30–42. https://doi.org/10.1016/j.compedu.2015.02.016

Parong, J., Mayer, R. E., Fiorella, L., MacNamara, A., Homer, B. D., & Plass, J. L. (2017). Learning executive function skills by playing focused video games. *Contemporary Educational Psychology*, *51*, 141–151. https://doi.org/10.1016/j.cedpsych.2017.07.002

Perone, S., Almy, B., & Zelazo, P. D. (2018). Toward an understanding of the neural basis of executive function development. In R. Gibb & B. Kolb (Eds.), *The Neurobiology of Brain and Behavioral Development* (pp. 291–314). Elsevier Inc. https://doi.org/10.1016/B978-0-12-804036-2.00011-X

Plass, J. L., Heidig, S., Hayward, E. O., Homer, B. D., & Um, E. (2014). Emotional design in multimedia learning: Effects of shape and color on affect and learning. *Learning and Instruction*, *29*, 128–140. https://doi.org/10.1016/j.learninstruc.2013.02.006

Plass, J. L., Homer, B. D., & Kinzer, C. K. (2015). Foundations of game-based learning. *Educational Psychologist*, *50*(4), 258–283. https://doi.org/10.1080/00461520.2015.1122533

Plass, J. L., Homer, B. D., MacNamara, A., Ober, T. M., Rose, M. C., Hovey, C. M., … Olsen, A. (2018). Emotional design for digital games for learning: The affective quality of expression, color, shape, and dimensionality of game characters. *Manuscript Submitted for Publication*.

Plass, J. L., & Kaplan, U. (2016). Emotional design in digital media for learning. In S. Y. Tettegah & M. Gartmeier (Eds.), *Emotions, Technology, Design, and Learning* (1st ed., pp. 131–161). New York, NY: Academic Press.

Poon, K. (2018). Hot and cool executive functions in adolescence: Development and contributions to important developmental outcomes. *Frontiers in Psychology*, *8*, 1–18. https://doi.org/10.3389/fpsyg.2017.02311

Powers, K. L., Brooks, P. J., Aldrich, N. J., Palladino, M. A., & Alfieri, L. (2013). Effects of video-game play on information processing: A meta-analytic investigation. *Psychonomic Bulletin and Review*, *20*, 1055–1079. https://doi.org/10.3758/s13423-013-0418-z

Prencipe, A., Kesek, A., Cohen, J., Lamm, C., Lewis, M. D., & Zelazo, P. D. (2011). Development of hot and cool executive function during the transition to adolescence. *Journal of Experimental Child Psychology*, *108*(3), 621–637. https://doi.org/10.1016/j.jecp.2010.09.008

Roughan, L., & Hadwin, J. A. (2011). The impact of working memory training in young people with social, emotional and behavioural difficulties. *Learning and Individual Differences, 21*(6), 759–764. https://doi.org/10.1016/j.lindif.2011.07.011

Ryan, R. M., Fauth, R. C., & Brooks-Gunn, J. (2006). Handbook of research on the education of young children. In B. Spodek & O. N. Saracho (Eds.) (pp. 323–346). Mahwah, NJ: Lawrence Erlbaum Associates.

Sarsour, K., Sheridan, M., Jutte, D., Nuru-Jeter, A., Hinshaw, S., & Boyce, W. T. (2011). Family socioeconomic status and child executive functions: The roles of language, home environment, and single parenthood. *Journal of the International Neuropsychological Society*, *17*(1), 120–132. https://doi.org/10.1017/S1355617710001335

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., & Toga, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience*, *6*(3), 309–315. https://doi.org/10.1038/nn1008

Sowell, E. R., Thompson, P. M., Leonard, C. M., Welcome, S. E., Kan, E., & Toga, A. W. (2004). Longitudinal mapping of cortical thickness and brain growth in normal children. *The Journal of Neuroscience*, *24*(38), 8223–8231. https://doi.org/10.1523/JNEUROSCI.1798-04.2004

Sowell, E. R., Thompson, P. M., Tessner, K. D., & Toga, A. W. (2001). Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: Inverse relationships during postadolescent brain maturation. *The Journal of Neuroscience*, *21*(22), 8819–29. https://doi.org/21/22/8819 [pii]

Steinberg, L. (2008). A social neuroscience perspective on adolescent risk-taking. *Developmental Review*, *28*(1), 78–106. https://doi.org/10.1016/j.dr.2007.08.002

Strobach, T., Frensch, P. A., & Schubert, T. (2012). Video game practice optimizes executive control skills in dual-task and task switching situations. *Acta Psychologica*, *140*, 13–24. https://doi.org/10.1016/j.actpsy.2012.02.001

Tucker, J. (1987). Psychology of color. *Target Marketing*, 40–49.

Tukey, J. W. (1977). *Exploratory data analysis.* (1st ed.). New York, NY: Pearson.

Um, E., Plass, J. L., Hayward, E. O., & Homer, B. D. (2012). Emotional design in multimedia learning. *Journal of Educational Psychology*, *104*(2), 485–498. https://doi.org/10.1037/a0026609

Valdez, P., & Mehrabian, A. (1994). Effects of color on emotions. *Journal of Experimental Psychology: General*, *123*(4), 394–409. https://doi.org/10.1037/0096-3445.123.4.394

https://doi.org/10.1080/87565641.2012.733786

von Bastian, C. C., & Eschen, A. (2016). Does working memory training have to be adaptive? *Psychological Research*, *80*(2), 181–194. https://doi.org/10.1007/s00426-015-0655-z

Welsh, J., Nix, R. L., Blair, C., Bierman, K. L., & Nelson, K. E. (2010). The development of cognitive skills and gains in academic school readiness for children from low-income families. *Journal of Educational Psychology*, *102*(1), 43–53. https://doi.org/10.1037/a0016738.The

Welsh, M., & Peterson, E. (2014). Issues in the conceptualization and assessment of hot executive functions in childhood. *Journal of the International Neuropsychological Society*, *20*, 152–156. https://doi.org/10.1017/S1355617713001379

Willcutt, E. G., Doyle, A. E., Nigg, J. T., Faraone, S. V., & Pennington, B. F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: A meta-analytic review. *Biological Psychiatry*, *57*(11), 1336–1346. https://doi.org/10.1016/j.biopsych.2005.02.006

Woltering, S., Lishak, V., Hodgson, N., Granic, I., & Zelazo, P. D. (2016). Executive function in children with externalizing and comorbid internalizing behavior problems. *Journal of Child Psychology and Psychiatry*, *57*(1), 30-38.

Yeniad, N., Malda, M., Mesman, J., van Ijzendoorn, M. H., & Pieper, S. (2013). Shifting ability predicts math and reading performance in children: A meta-analytical study. *Learning and Individual Differences*, *23*, 1–9. https://doi.org/10.1016/j.lindif.2012.10.004

Zelazo, P. D. (2006). The Dimensional Change Card Sort (DCCS): A method of assessing executive function in children. *Nature Protocols*, *1*(1), 297–301. https://doi.org/10.1038/nprot.2006.46

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-Allen, K., Beaumont, J. L., & Weintraub, S. (2013). NIH toolbox cognition battery (CB): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. https://doi.org/10.1111/mono.12032

Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. *Child Development Perspectives, 6*(4), 354–360. https://doi.org/10.1111/j.1750-8606.2012.00246.x

Zelazo, P. D., & Lyons, K. E. (2011). Mindfulness training in childhood. *Human Development*, *54*, 61–65. https://doi.org/10.1159/000327548

Zelazo, P. D., & Müller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.) (pp. 445–469). Oxford: Blackwell.

Zinke, K., Einert, M., Pfennig, L., & Kliegel, M. (2012). Plasticity of executive control through task switching training in adolescents. *Frontiers in Human Neuroscience*, *6*, 1–15. https://doi.org/10.3389/fnhum.2012.00041