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ORIGINAL ARTICLE

Child's Play? Assessing the Bidirectional Longitudinal Relationship between Gaming and Intelligence in Early Childhood

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This study investigated the longitudinal relationship between children's digital game use and fluid and crystallized intelligence. Specifically, this study examined whether digital games affect children's fluid and crystallized intelligence (an effects perspective), whether children with higher levels of fluid or crystallized intelligence are more attracted to digital games (a selection perspective), or whether evidence supports a reciprocal relationship between digital game play and intelligence. Using data from 934 children aged 3 to 7 years (52% girls) across four waves with one-year intervals, our evidence for fluid intelligence indicates partial support for the effects perspective and no support for the selection perspective. For crystallized intelligence, our findings did not reveal any significant relationship with digital game use. The results suggest that digital games can move the needle for fluid intelligence, but more insight is needed to identify how this effect occurs, in which situations, and for which children this is most likely.

Keywords: Crystallized Intelligence, Digital Games, Early Childhood, Fluid Intelligence, Media.

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Over the past decades, a considerable number of studies have shown increases in intelligence when generations of children and adolescents are compared with previous ones (Flynn, 1987; Lynn, Hampson, & Mullineux, 1987). Coined the Flynn Effect in recognition of its namesake, James Flynn was the first to demonstrate that, starting in the 1950s, youths' intelligence began to steadily increase across the industrialized world. This increase seems to be particularly pronounced for fluid intelligence (i.e., the ability to analyze novel problems, identify the patterns and relationships that underlie problems, and solve these problems using logic), whereas

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smaller increases have been reported for crystallized intelligence (i.e., the ability to access information from long-term memory, often referred to as general knowledge; Flynn, 1987; te Nijenhuis, 2013).

The question is: what might explain this increase in children's fluid intelligence? One likely explanation is that the increase in intelligence reflects environmental changes, including changes in the media landscape (Flynn, 2009). Indeed, the second half of the 20th century has witnessed the rise and widespread adoption of media use throughout childhood, and this media space has become faster, more complex, and—thanks to the rise of digital games—increasingly interactive (Powers, Brooks, Aldrich, Palladino, & Alfieri, 2013). Today's children have far more opportunities than earlier generations to spend their leisure time on cognitively-demanding pursuits. Most notably, the richer interactive gaming space offers children an experience whereby their visuospatial, logic, and problem-solving abilities are naturally called upon (for a discussion, see Jackson et al., 2012). This experience may potentially explain the rise in children's fluid intelligence. Supporting this idea, meta-analyses have found small, positive relationships between game play and fluid intelligence–related outcomes (e.g., problem solving, reasoning) among samples of adolescents and (mostly) adults (Bediou et al., 2018; Powers et al., 2013; but see Sala, Tatlidil, & Gobet, 2017).

That said, while it may be the case that game playing provides a form of so-called "brain training," which ultimately enhances children's fluid intelligence, communication scholars have aptly argued for the reverse process as well. Specifically, theoretical models such as selective exposure theory (Klapper, 1960; Knobloch-Westerwick, 2015) or the differential susceptibility to media effects model (Valkenburg & Peter, 2013) suggest that individuals are more likely to select media that are congruent with their own skills or background. Since games naturally require visual, logic, and problem-solving skills to succeed, scholars in favor of this paradigm would argue that children who have strong fluid intelligence will be more likely to select and play digital games. Moreover, neither explanation precludes the other. After all, a child who frequently uses digital games may experience an increase in fluid intelligence and, as a result, may become even more attracted to playing the games that further exercise those abilities. Yet, despite existing scholarship on gaming and intelligence (cf. Bediou et al., 2018; Powers et al., 2013; Sala et al., 2017), and despite investigations that compare changes in intelligence across generations (Flynn, 1987), no longitudinal studies exist that investigate these reciprocal relationships between gaming and fluid intelligence within a generation of young children.

To address this gap in the literature, we used data from a four-wave longitudinal study, across four years, with 934 children between the ages of three to seven at the time of study onset to investigate the reciprocal longitudinal relationships between children's digital game play and intelligence. Our focus on these young children is important and timely in two respects. First, the current generation of children is now beginning to use media at ever-younger ages. Whereas in the 1970s, the average age that a child started using media was around four years of age, today's children begin around four months of age (Valkenburg & Piotrowski, 2017). Second, the availability of digital games for the early childhood demographic has been significantly boosted in the new millennium, in large part due to the introduction of touchscreen technology, which is the first technology to optimally accommodate the cognitive and motor skills of children in early childhood. Therefore, these very young children—dubbed Gen alpha (born since 2010)—are the first to experience the potential cognitive benefits of digital game play at the earliest and most impressionable period in human life.

Delineating "gaming" and "intelligence"

The potential links between gaming and intelligence-related constructs have been investigated across several disciplines, including psychology, neurology, communication science, and game studies. The challenge with this interdisciplinary interest is that different disciplines operationalize gaming and intelligence in diverse ways. Here, we focused on children's digital game play, regardless of the genre (e.g., educational, violent, entertainment) or platform used (e.g., game console, desktop computer, handheld device, or smartphone). Moreover, we did not focus on the effects of game *training* (i.e., games designed with the specific goal to improve cognitive skills, such as *NeuroRacer* or *Brain Age*), but on naturally occurring game play in children's everyday lives (i.e., time spent playing games). That said, we did rely on game-training literature and scholarship with adolescents and adults, since these topics and populations occur more frequently in the literature.

Intelligence is notoriously difficult to define (Schneider & McGrew, 2013). In this study, we focused on the distinction between fluid and crystallized intelligence. In our review, however, we found that a large part of the literature on digital games and intelligence has focused on several more specific cognitive abilities that are closely related (though not identical) to fluid intelligence, such as working memory, processing speed, or visuospatial skills (Dye, Green, & Bavelier, 2009; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Mackey, Hill, Stone, & Bunge, 2011). Work on these related cognitive skills is discussed when it sheds light on the processes in which games may be related to intelligence.

Digital game play as a predictor of intelligence (media effects perspective)

Because games seem to inherently and effortlessly rely on cognitive abilities, the idea that playing digital games can support intelligence—particularly fluid intelligence—seems intuitively logical. Yet, pinpointing *how* games may do so is less clear-cut, because no clear theoretical frameworks exist to explain how game play may support intelligence. However, two categories of empirical studies—namely, cognitive training and commercial games studies—offer some guidance as to how and why games may support fluid intelligence.

Cognitive training and fluid intelligence

In neuroscience and related fields, studies on cognitive training have increasingly focused on the potential of gamified tasks to "train the brain" (e.g., Neugnot-Cerioli, Gagner, & Beauchamp, 2017; Owen et al., 2010). Cognitive training refers to interventions that offer "structured practice on tasks relevant to different aspects of cognitive functioning" (Toril, Reales, & Ballesteros, 2014, p. 706). Such training typically relies on well-known cognitive tests that have been computerized or gamified (e.g., Dörrenbächer, Müller, Tröger, & Kray, 2014). In other words, the tasks used in these brain-training studies are typically "tests first, games second" (i.e., cognitive tests which are then turned into games).

In these studies, the created brain games focus on tasks that are often used to assess fluid intelligence, such as pattern recognition, the identification of logical rules, and the application of these results to novel situations (Baniqued et al., 2013; Bergman Nutley et al., 2011; Söderqvist, Bergman Nutley, Ottersen, Grill, & Klingberg, 2012). Although studies vary, the majority employ an experimental format, with repeated play of brain games serving as the independent variable and cognitive skills as the outcome of interest. While a number of studies within this domain have shown improved fluid intelligence skills as a result of brain training (e.g., Bergman Nutley et al., 2011; Mackey et al., 2011; Neugnot-Cerioli et al., 2017), others have shown no transfer effects (i.e., improvement on the trained skill, but no effects on more general fluid intelligence) or no effects at all (e.g., Baniqued et al., 2013). Indeed, a comprehensive review of the brain-training literature suggests that brain training is most effective at improving performance on trained tasks, whereas its effects are less pronounced for closely-related tasks and nearly nonexistent for distantly-related tasks (Simons et al., 2016). However, in the same vein, this review acknowledges many methodological caveats to the field writ large (e.g., issues with design or analysis) that prohibit definitive conclusions about the transfer potential of brain training.

Cognitive psychologists hypothesize that, ultimately, brain training may result in changes in the brain regions that support processes related to fluid intelligence (Mackey et al., 2011; Shams et al., 2015). To our knowledge, only one study has actually tested whether a game designed to tap into fluid intelligence–related abilities indeed resulted in such neural changes. Anguera and colleagues (2013) experimentally showed that playing a custom-designed video game that manipulated single-tasking versus multi-tasking improved older adults' working memory and sustained attention (i.e., skills associated with fluid intelligence; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Electro-encephalogram technology demonstrated that game play led to increased electrical activity in participants' medial prefrontal cortex, as well as in the connections between the frontal and posterior regions of the brain. These areas of the brain are associated with attributes underlying fluid intelligence, including working memory and sustained attention. Anguera et al. (2013) suggested that well-designed games may strengthen this part of the brain, potentially explaining their benefits for fluid intelligence (see also Jaeggi et al., 2008, for evidence to support a transfer effect).

Commercial games and fluid intelligence

Next to brain-training research, a second category of empirical work has focused on the cognitive benefits of playing commercial games (i.e., games not developed with the specific goal of training cognitive skills). In this domain, action games are the most frequently studied, often in samples of adolescents or adults. Researchers hypothesize that a wide range of cognitive outcomes can benefit from action games' typical features: namely, their fast pace; the high degree of perceptual and motor loads; the working memory, planning, and goal setting requirements; the required constant switching between focused and broader attention; and a high degree of clutter and distraction (Bavelier, Green, Pouget, & Schrater, 2012). In support of this, a recent meta-analysis by Bediou et al. (2018) showed that action game play was related to several cognitive outcomes (e.g., perception, attention, multi-tasking). However, neither Bediou et al.'s meta-analysis on action games, nor a meta-analysis by Sala et al. (2017) on general game play found that game play was significantly related to fluid intelligence or related concepts (i.e., problem solving, reasoning).

In these two meta-analyses, there is a notable lack of studies on gaming and fluid intelligence among children and adolescents. However, in the few studies among these age groups that do exist, the weight of evidence seems to point to the beneficial effects of digital game playing on fluid intelligence (but see Lieury et al., 2016). Three studies have found that children and adolescents who played games (whether operationalized as self-report or as game play in an experimental condition) scored higher on fluid intelligence measures, compared to those who played no or fewer games (mean age 14.7 years, Gnambs & Appel, 2017; youth between 7 and 9 years, Mackey et al., 2011; youth between 12 and 16 years, Neugnot-Cerioli et al., 2017). Two other studies found that beneficial effects were limited to certain types of game play. For example, a longitudinal study among 13- to 16-year-olds yielded positive effects on fluid intelligence, but only for strategic game play, and not for fast-paced game play (Adachi & Willoughby, 2013). A study among 3- to 5-year-olds found a positive relationship between game access (i.e., having a computer available at home or somewhere else) and fluid intelligence, but no such relationship between frequency of game play and fluid intelligence (Li & Atkins, 2004).

As for underlying mechanisms, unlike the brain-training scholarship, commercial game research has focused less on how games can train specific cognitive outcomes through neural changes (but see Bavelier et al., 2012). However, implicit in the commercial gaming literature is the idea that features inherent to commercial games allow for the practice and subsequent strengthening of fluid intelligence skills (akin to the argumentation posited for brain-training effects). Although the exact (neural) mechanisms to explain the effects of commercial games are still being posited, tested, and debated (Bavelier et al., 2012; Sala et al., 2017), it seems reasonable to expect that commercial games, too, have the potential to support fluid intelligence in similar ways as brain games, given that most commercial games today rely on some aspects of fluid intelligence for success (e.g., pattern recognition, rule deduction, visuospatial skills). As such, we posited the following hypothesis:

> H1: An increase in children's game play results in a subsequent increase in children's fluid intelligence over time (media effects hypothesis).

Games as predictor of crystallized intelligence

The majority of studies on gaming and intelligence focus on the cognitive abilities associated with fluid intelligence (cf. Bediou et al., 2018; Sala et al., 2017), rather than crystallized intelligence. This is consistent with Flynn's (2009) expectations that the increased complexity of today's children's environment—including the media environment—may explain specific increases in youths' cognitive *skills*, and not necessarily (or automatically) their level of *knowledge* about the world. Yet, if we wish to understand whether gaming should be considered as one of the explanations for the specific rise in *fluid* intelligence, work that compares whether these effects also hold for crystallized intelligence is needed. To that end, we also asked:

> RQ1: Is an increase in children's game play related to a subsequent increase in crystallized intelligence over time (media effects question)?

Intelligence as a predictor of digital game play (media selection perspective)

While the majority of scholarship in the area of gaming and intelligence has focused on an effects paradigm, the reverse process is also conceptually likely. Communication scholarship has long acknowledged that individuals, as a result of their disposition, have their own particular needs or motivations for media use (Katz, Blumler, & Gurevitch, 1973; Klapper, 1960; Knobloch-Westerwick, 2015). Referred to as disposition-content congruency (Valkenburg & Peter, 2013), the argument is that individuals tend to seek out media activities that match their existing dispositions. During such activities, this experience is interpreted as more positive and aesthetically pleasurable than a dispositionally-incongruent activity (i.e., hedonic fluency hypothesis; Reber, Schwarz, & Winkielman, 2004), which may encourage continued or repeat use.

In this context, one's intelligence may result in particular needs or motivations, which gaming can potentially fulfill. Well-designed games are said to require users to switch tasks and/or perspectives and to consider different options, all in an effort to solve a "pleasantly frustrating" problem or set of problems that "continually challenges the player within his or her abilities" (Valkenburg & Piotrowski, 2017, p. 202–203; see also Gee, 2006). Research has shown that fluid intelligence predicts certain skills that are inherent to successful game play, such as one's ability to multitask (Konig, Buhner, & Murling, 2005), to engage in divergent thinking and creative cognition (Batey, Furnham, & Safiullina, 2010; Silvia & Beaty, 2012), and to solve problems (Swanson, Jerman, & Zheng, 2008; Xin & Zhang, 2009). Thus, for children with higher fluid intelligence, games may offer an effective and pleasant way of using one's cognitive skills.

The literature to test this selection perspective is limited compared to effects research. A correlational study by Hamlen (2013) found that fourth- and fifth-grade children with greater practical (but less creative) problem-solving abilities were more likely to play video games. A study with adults noted that fluid intelligence (and its related attributes) is positively correlated with successful game performance (e.g., Baniqued et al., 2013). These findings are in line with the selective exposure argument that, for users with increased fluid intelligence, games can fulfill their need for cognitive challenge. Research on game play motivations (e.g., uses & gratifications scholarship) would also concur with this sentiment. In fact, several studies have shown that cognitive challenges are often a motivational factor behind their play (e.g., "I like the challenge of figuring the game out," "Repeating levels bores me. I hate games that you always start at the beginning"; Ferguson & Olson, 2013; Sherry, Lucas, Greenberg, & Lachlan, 2006; Wu, Wang, & Tsai, 2010).

To our knowledge, only one study has attempted to assess the directionality over time of the gaming/fluid intelligence relationship. Adachi and Willoughby (2013) longitudinally investigated whether 13- to 16-year-olds' fluid intelligence (operationalized as adolescents' self-reported problem-solving abilities) predicted subsequent game play, or vice versa. They found no evidence for a selection effect over time, but only a media effect (i.e., strategic game play predicted subsequent problem-solving abilities). Overall, then, while the theoretical argumentation for the selection perspective on gaming and fluid intelligence is reasonable, the body of empirical literature testing this supposition is small. To address this gap, we investigated the extent to which fluid intelligence predicts children's game play over time. Guided by predictions of selective exposure theory, we posited the following hypothesis:

> H2: An increase in children's fluid intelligence results in a subsequent increase in game play over time (media selection hypothesis).

Crystallized intelligence as a predictor of gaming

While the underlying argumentation for fluid intelligence as a predictor of game play is reasonably robust, it is more difficult to understand how crystallized intelligence (i.e., general knowledge) may result in more time spent playing digital games, irrespective of content. Based on educational media literature, we may anticipate that children who have relatively more acquired knowledge in a specific domain may be motivated to seek out games with content that maps onto that knowledge, but not necessarily to spend more time playing games in general. However, for a complete investigation of the causal relationship between gaming and intelligence, we also tested the following research question:

> RQ2: Is an increase in children's crystallized intelligence related to a subsequent increase in game play over time (media selection question)?

Reciprocal processes

Of course, while it may be the case that any relationship between children's game play and intelligence could be explained via either an effects or a selection paradigm, it is quite possible that both processes may be at play. After all, game play may offer children rehearsals of the skills needed to build and support intelligence and, in turn, these skills may lead to an increased preference for game play by virtue of disposition-content congruency (Slater, 2007; Valkenburg & Peter, 2013). To address this, we investigated whether a reciprocal relationship exists between children's game play and both types of intelligence:

> RQ3: Is there a reciprocal relationship between children's game play and fluid intelligence over time?
> RQ4: Is there a reciprocal relationship between children's game play and crystallized intelligence over time?

Method

Participants and procedure

The data for this study were collected as part of a large, longitudinal project into children's media use. After receiving approval from the sponsoring institution's Institutional Review Board, a private survey research institute collected the data. Families were recruited through the company's existing online panel of approximately 60,000 households, which are representative of the Netherlands. All households with at least two children between 3 and 7 (1,746 families in the panel) were invited to participate, and 521 families did participate. Data collection consisted of four waves and took place in the fall seasons of 2012, 2013, 2014, and 2015. In each data wave, trained interviewers visited the participants' homes, where parents completed a survey that included questions on their children's digital game use, while children completed two standardized cognitive tasks with the interviewers. A total of 934 children between 3 and 7 years (M_{age} = 5.41 years, SD_{age} = 1.40 years; 52.0% girls) participated in Wave 1 (total number of participating children in Wave 2 = 890; Wave 3 = 842; Wave 4 = 830).

Measures

Children's digital game use

Children's digital game use was measured through parent-reported direct estimates, which are commonly used in large survey studies (Vandewater & Lee, 2009) and have been validated in previous work (Fikkers, Piotrowski, & Valkenburg, 2017). Parents were first provided with a definition of digital games that included all types of games (e.g., games played on computer or game consoles, but also casual games played on mobile phones or websites). They then answered two questions. The first item measured frequency of use, and asked: "On how many days per week does your child play digital games?" This question was answered on a scale from 0 (never) to 7 (7 days per week). The second item measured duration, and asked: "And on the days that your child plays digital games, how much time does he/she spend on this?" This was an open-ended item, whereby parents reported hours and minutes per day of media use. We multiplied frequency and duration to arrive at a number of hours per week of digital game use.

Fluid and crystallized intelligence

To measure the two types of intelligence, we selected two standardized tasks from the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-III; suitable for children aged 2:6 to 7:11) and the Wechsler Intelligence Scale for Children (WISC-III; suitable for children aged 6:0 to 16:11). From both sets, we used the block pattern task to assess fluid intelligence (visual, logic, problem-solving abilities) and the information task to assess crystallized intelligence (fact-based knowledge). The block pattern task provides an indication of children's fluid intelligence through a series of models or pictures of block patterns that children need to reconstruct with their own blocks within a specified time limit. The information task provides an indication of children's crystallized intelligence by asking them a series of factual questions that increase in difficulty. Both tasks proceed until a child has reached a predetermined number of wrong answers, at which point the test is finished.

During the home visit, interviewers scored children's performance on the two tasks on standardized paper forms. After the data collection, all paper forms were checked for any irregularities. In the first wave, all children completed the tasks from the WPPSI; in subsequent waves, increasing numbers of children aged into the WISC tasks. Validation research showed that correlations between the same tasks on the WPPSI and the WISC are high (block pattern task: $r = .74$; information task: $r = .80$; Hendriksen & Hurks, 2009), offering support for this study's approach of starting with the WPPSI and then following up with the WISC in subsequent waves. In Wave 1, reliable score forms were collected for 855 children for the block pattern task and 848 children for the information task (Wave 2 = 816/820; Wave 3 = 745/809; Wave 4 = 730/796). Raw scores for each task were converted into scaled or norm scores per age group, which were normally distributed. Norm scores have a possible range from 0–19, a mean of 10, and a standard deviation of 3 (Hendriksen & Hurks, 2009). The means and standard deviations for our sample are reported in Table 1. In the analyses, the norm scores that resulted from the WPPSI and the WISC were analyzed together. Cross-sectional zero-order correlations between fluid and crystallized intelligence in the four waves ranged between .37 and .44 (p's $< .001$).

Analytic approach

Analyses were conducted in Mplus 7.31 (Muthén & Muthén, 2014). To appropriately model the reciprocal relationships between children's digital game use and their cognitive performance, we ran two separate Random Intercept Cross-Lagged Panel Models (RI-CLPMs): one for fluid intelligence and one for crystallized intelligence. RI-CLPMs have recently been identified as the most appropriate analyses to analyze within-person relationships between two variables over time (Hamaker, Kuiper, & Grasman, 2015; Keijsers, 2016). Although traditional cross-lagged panel models control for temporal stability of variables through the inclusion of autoregressive relationships, such models assume that all participants in a sample vary around the same mean over time. This ignores the role of unique within-person

Table 1 Means (SDs) and Zero-Order Correlations for Digital Game Use and Intelligence

	Wave 1	Wave 2	Wave 3	Wave 4
Digital game use[a]	1.96 (3.30)	2.38 (2.99)	3.12 (3.94)	4.15 (4.82)
Fluid intelligence[b]	10.42 (3.02)	11.03 (2.94)	11.23 (3.09)	11.80 (3.12)
Crystallized intelligence[b]	10.89 (3.02)	11.27 (2.71)	11.31 (2.63)	11.67 (2.61)
Cross-sectional correlations[c]				
Games with fluid intelligence	.05	.06	.10*	.10*
Games with crystallized intelligence	−.01	.13*	.07†	.06

*$p < .05$; †$p < .10$
[a]Hours per week.
[b]Norm scores (i.e., raw scores converted into a scaled score based on a child's age group).
[c]Pearson's r correlations, converted from Kendall's tau-a correlations using Greiner's relation in Stata 12 (Newson, 2002).

processes, which is a problematic assumption in developmental research (Hamaker et al., 2015; Keijsers, 2016). In contrast, RI-CLPMs take a multilevel approach by allowing individuals to vary around their own mean, which results in better estimates of within-individual dynamics between two variables. By controlling for time-invariant, trait-like individual differences (Hamaker et al., 2015), all inter-individual differences are captured by the model. More detailed information about this approach can be found in Hamaker et al. (2015). Of note, analyzing data using an RI-CLPM may result in different findings than those previously obtained using classic statistical models (see, e.g., Keijsers, 2016, for a comparison of findings using cross-lagged panel models and RI-CLPMs).

Given the open-ended nature of the digital game use measure, this variable was inspected for outliers using a common statistical operationalization of outliers, defined as scores falling outside the mean plus three standard deviations (Tabachnick & Fidell, 2007). This approach indicated that in Waves 1 to 4, scores above 11.86, 11.36, 14.94, and 18.63 hours per week (18, 13, 17, and 14 cases, respectively) constituted statistical outliers. However, in our view, these values do not represent outliers in practice, especially because a large sample of children, such as our sample, can reasonably include children that score higher on digital game use by nature of their disposition. We therefore chose to report the results based on the original data, which included these statistical outliers. We also ran models in which digital game exposure outliers were recoded to the mean plus three standard deviations. In these models, no coefficients changed from significant (i.e., $p < .05$) to non-significant ($p > .05$) or vice-versa.

To account for skewness of the game variable, we used full-information maximum likelihood estimations with robust standard errors (Muthen & Satorra, 1995). The model fit was evaluated using the model Chi-square, the Root Mean Square Error of Approximation (RMSEA), the Comparative Fit Index (CFI), and Tucker-Lewis Index (TLI). A good model fit is indicated by a non-significant Chi-square value (although large samples such as ours often do result in significant Chi-squares), an RMSEA smaller than .05, and CFI and TLI measures larger than .95 (Kline, 2011). Mplus outputs can be found at the authors' websites. The data used for this article can be requested from the third author.

Results

Descriptives and correlations

Table 1 reports the means for fluid and crystallized intelligence; hours per week of children's digital game use, as reported by the parent; and the cross-sectional correlations between intelligence and digital game use. Intelligence scores increased slightly across waves, from a mean of 10.42 ($SD = 3.02$) in Wave 1 to 11.78 ($SD = 3.12$) in Wave 4 for fluid intelligence. Crystallized intelligence scores increased from a mean of 10.89 ($SD = 3.02$) in Wave 1 to 11.67 ($SD = 2.61$) in Wave 4. Children's digital game exposure started at an average of 1.96 hours per week in Wave 1 ($SD = 3.30$ hours) and increased to an average of 4.15 hours per week by Wave 4 ($SD = 4.82$ hours).

Within-wave cross-sectional correlations showed that digital game use was positively related to fluid intelligence in Waves 3 and 4 (but not Waves 1 and 2), and to crystallized intelligence in Wave 2. Stability correlations between digital game play scores across the four waves ranged between .47 and .60 (p's $< .001$). For fluid intelligence, stability correlations ranged between .51 and .69 (p's $< .001$). Correlations between crystallized intelligence scores across the four waves ranged between .48 and .59 (p's $< .001$).

Longitudinal bidirectional relationship between gaming and fluid intelligence

The RI-CLPM testing the relationship between digital game use and fluid intelligence (H1; H3) showed a good model fit ($\chi^2[9] = 17.284$; $p = .044$; RMSEA = .031; CFI = .992; TLI = .974). The results are presented in Figure 1.[1] Children who used more games relative to their own average in Wave 2 had higher than their own average scores on fluid intelligence in Wave 3 ($beta = .110$, $SE = .050$, $p = .027$). Media effects of game play on fluid intelligence were not significant between Waves 1 and 2 ($beta = -.025$; $SE = .086$; $p = .774$) or between Waves 3 and 4 ($beta = .071$; $SE = .039$; $p = .068$). This offered partial support for H1 (media effects for fluid intelligence). Across waves, within-child deviations in fluid intelligence did not predict subsequent within-child deviations in digital game use. As such, H2 (media selection for fluid intelligence) was rejected. Finally, because our findings do not illustrate both an effects and selection perspective, this study did not find support for a reciprocal relationship between children's game play and fluid intelligence (RQ3).

Longitudinal bidirectional relationship between gaming and crystallized intelligence

The model for crystallized intelligence also showed a good model fit ($\chi^2[9] = 18.062$; $p = .035$; RMSEA = .033; CFI = .990; TLI = .968). The results are presented

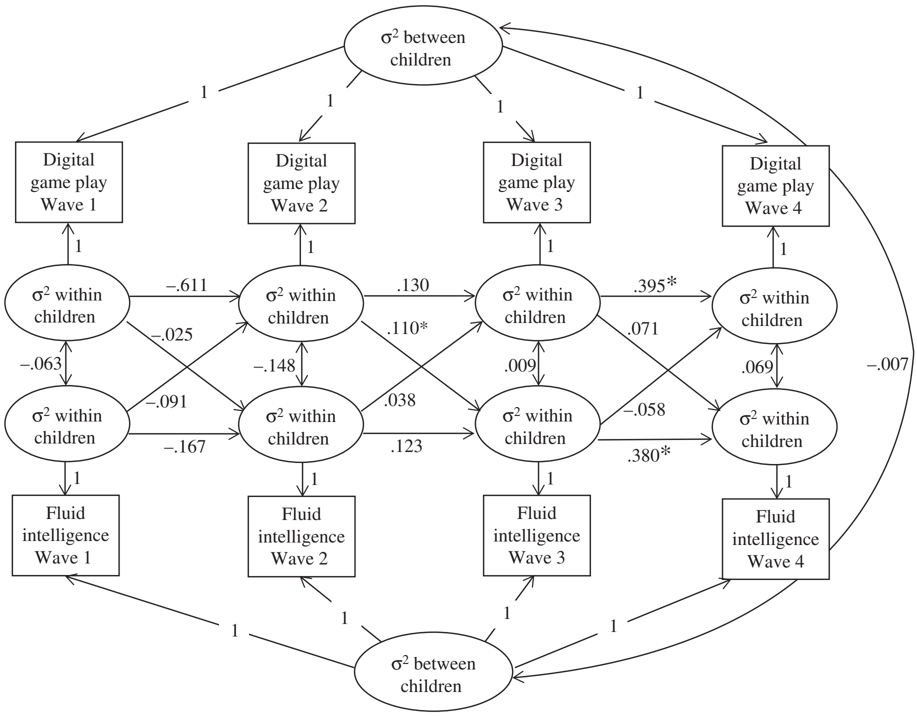

Figure 1 Random intercept cross-lagged panel model for the relationship between digital game play and fluid intelligence (standardized coefficients). Cross-lagged parameters in a random intercept model represent the relationship between an individual's temporal deviations from their expected media use scores and subsequent deviations from their expected intelligence scores (Hamaker et al., 2015). $^*p < .05$.

in an online Supplemental Figure. No significant longitudinal relationships were found between within-child deviations in digital game use and within-child deviations in crystallized intelligence. Thus, in response to RQ1, RQ2, and RQ4, this study did not find any relationships between game play and crystallized intelligence over time.

Discussion

This study was, to our knowledge, the first to investigate the longitudinal relationship between young children's digital game play and their fluid (problem-solving abilities) and crystallized intelligence (fact-based knowledge). It was also the first to investigate whether this relationship is best characterized from an effects or a selection perspective, or both. For fluid intelligence, the results partly confirmed the effects perspective, with children's digital game play in Wave 2 predicting fluid intelligence scores in Wave 3. Contrary to our expectations, the selection perspective (and therefore also the reciprocal relationship) was not supported for fluid intelligence.

Although the earlier literature did not give reason to expect a relationship between digital game play and crystallized intelligence, by way of comparison, we also explored this longitudinal relationship. As anticipated, no significant relationships between digital game play and crystallized intelligence were found. These findings support earlier accounts on the gaming/intelligence relationship, which argue that children's digital media environments may lead to increases in the cognitive skills that underlie fluid intelligence, but not necessarily to increases in their general, fact-based knowledge (Greenfield, 1998). Our results also support explanations that argue that complex environmental stimuli, such as digital games, may be partly responsible for the Flynn effect (i.e., the consistent evidence for increases in children's fluid intelligence since the 1950s; Flynn, 2009).

Already in the 1990s, scholars began noting that certain tasks in contemporary digital games resemble the tasks in fluid intelligence tests (Greenfield, 1998). For example, in the block pattern test that we used in our study, young children needed to reconstruct block patterns within a specific time limit from models built by an adult or shown in a picture book. Indeed, this block pattern test may call upon cognitive capacities (e.g., recognition of rules, spatial awareness, and processing speed) that are similar to the tasks needed to successfully complete digital games. Our results are in line with those from earlier studies among older age groups, showing that digital games have the potential to train certain cognitive skills that underlie fluid intelligence and, by doing so, to increase this type of intelligence (e.g., Mackey et al., 2011; Neugnot-Cerioli et al., 2017).

Bridging micro and macro approaches to investigate game-induced cognitive abilities

Despite the intuitive appeal of the brain-training explanation, the mechanisms through which digital game play may increase fluid intelligence still require improved theorizing. In this study, we mainly relied on studies on the effects of cognitive training and commercial games to build our argumentation. However, this work typically zooms in on specific elements of gaming by asking, for example, whether pattern recognition or constant switching between tasks enhance closely-linked cognitive skills via neural activation (Baniqued et al., 2013; Bavelier et al., 2012; Bergman Nutley et al., 2011; Powers et al., 2013). This micro-level focus on particular game elements is certainly helpful, especially when trying to identify neural mechanisms. But there is a clear tension between the scientific need to understand how specific game features support cognitive skills and the societal, macro-level need to understand how everyday gaming is related to long-term cognitive outcomes in everyday life.

Given this tension, there is a clear need for future work that bridges this gap between micro- and macro-level scholarship to understand the relative role of digital game play in children's lives, as well as to identify which children are most (or least) likely to benefit and why. Such scholarship will likely be circular in nature. Game training research can continue working to identify those key features that are linked with neural changes and fluid intelligence on a micro-level. In doing so, they can help answer questions about whether such specific training benefits may transfer to broader cognitive abilities (Bavelier et al., 2012; Jaeggi et al., 2008) or not (Sala et al., 2017), or how game play can best be structured to keep supporting intelligence after the initial learning effects (e.g., through extended and variable game training; Kranz, Baniqued, Voss, Lee, & Kramer, 2017).

Following this, in order to move from micro-level to macro-level patterns, scholars could use the knowledge developed in the brain-training studies to develop content-analytic work that identifies the presence of these features in existing commercial games. This content-analytic information can then be linked to children's intelligence scores via large-scale (longitudinal) studies (i.e., linkage analysis; Scharkow & Bachl, 2017). Such work would be ideally suited to test whether the relationship between gaming and fluid intelligence is more robust when children engage more frequently with games that rely on fluid intelligence–promoting features. For example, in the related field of creativity, scholars have shown that games with action elements are more likely to result in creativity (particularly flexibility) than games without action features (Yeh, 2015). In much the same way, there may be other, specific features of (certain) games that are more (or less) likely to promote fluid intelligence.

Even more, by also capturing relevant developmental, dispositional, and social individual differences, scholars would be able to understand whether particular children are more (or less) likely to benefit from (or be attracted to) such game features, potentially resulting in more pronounced effects (Valkenburg & Peter, 2013). Across childhood, developmentally changing constructs—such as theory-of-mind, broader executive functioning, but also changing media use and media literacy skills—may moderate the relationship between gaming and fluid intelligence. For example, in the early years, limited theory-of-mind or media literacy skills may minimize the benefits of gaming, whereas once these skills are developed, older children may be better able to capitalize on their potential (cf. DeLoache, 2011; Lapierre, 2015; Potter, 2013). This may partly explain why our study did not see a significant relationship between game play at Wave 1 and fluid intelligence at Wave 2. Similarly, there are likely other trait variables (e.g., curiosity; Kim & Lee, 2017) or social variables (e.g., parental mediation; Nikkelen, Vossen, Piotrowski, & Valkenburg, 2016) that may also augment the patterns detected here. Although large-scale longitudinal work (including our study) is less well suited to test (neural) mechanisms compared to micro-level research, such work can take into account the broader context of children's lives and, therefore, better speak to often-asked questions about the balance between screen- and non-screen–related activities (Jordan, 2004).

It is likely that such macro-level work will result in new questions that can be fed back to more fine-grained (brain-related) game research. Within communication science, the introduction of neuroscientific approaches has already inspired micro-level studies as to the relationship between gaming and outcomes. For example, Weber, Ritterfeld, and Mathiak (2006) conducted a frame-by-frame, event-related content analysis of adults' violent game play, which was then linked to the neural activation patterns associated with aggression through functional magnetic resonance imaging. Looking ahead, combined efforts to identify the neural mechanisms that explain the effects of gaming features and to apply the resulting knowledge to questions related to children's everyday life will be key to answering both theoretical and societal questions.

Methodological refinement for future research

The methodological setup of this longitudinal study offers several strengths, such as the availability of four waves of data (enabling state-of-the-art analytic models), a large sample of children across early childhood, and the inclusion of two standardized tasks of fluid and crystallized intelligence. At the same time, several points of improvement can be offered for future research. First, in this study, children's digital game play was measured through a parent-report scale, which captured the number of hours spent playing digital games per week. For this particular study, such a generalized measure was a conceptually appropriate match to our hypotheses, given that previous research and meta-analyses have shown that the game-induced increases in cognitive skills can occur across game types (Powers et al., 2013). However, as we learn more about the exact features of games that support fluid intelligence, hypotheses and corresponding game-play measures will need to become more specific in measuring differential experiences with specific game features.

Similarly, measurements of fluid intelligence could also benefit from refinement in the years ahead. Most gaming studies either measure fluid intelligence via intelligence (sub)tests (the approach taken in this study) or via related cognitive constructs, such as working memory, executive function, visuospatial skills, or problem solving (see, for example, Au et al., 2015; Powers et al., 2013). However, until now the literature has not yet reached consensus about how well such indicators reflect the omnibus construct of fluid intelligence. There is a need for future research that carefully reflects on what cognitive attributes are most susceptible to change as a result of digital game play. This will likely result in a move away from global assessments towards specific indicators of fluid (and crystallized) intelligence. In addition, the further application of RI-CLPMs in media use and effects research will help advance our understanding of between- and within-person processes for these two constructs over time.

Conclusion

When looking at differences in childhood across generations, evidence indicates that today's children are smarter than previous generations of children (Flynn, 2009) and that they are growing up in environments in which digital media use is part and parcel of their everyday lives (Common Sense Media, 2017). Our longitudinal findings indicate that digital game use can increase children's fluid intelligence, although the results were not entirely consistent across waves. Improved theorizing, measurement, and operationalization of constructs may help us get closer to a sophisticated understanding of the opportunities of digital games during childhood. And such work is necessary. Digital games are here to stay, and as children increasingly complement their analogue play experiences with digital game play, it will become even more imperative to understand how these experiences may benefit young users.

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Note

1 As can be seen in Figure 1, the model results in nonsignificant, negative within-person stability coefficients between Waves 1 and 2. To rule out the possibility that these nonsignificant coefficients were caused by artefacts in our data set or analyses, we ran additional analyses in which we tested the model for different age groups and for those children who completed the WPSSI block pattern task in all four waves. The results indicated that the nonsignificant stability coefficients between Waves 1 and 2 are not due to our specification of the analytic model, the children's age, or switching from the WPPSI to the WISC block pattern task. Further work to understand within-subjects processes in (particularly) fluid intelligence, as measured by the block pattern task, is necessary.

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