International Journal of Child-Computer Interaction 34 (2022) 100534

Contents lists available at ScienceDirect

International Journal of Child-Computer Interaction

journal homepage: www.elsevier.com/locate/ijcci

Research paper

A comparison of the impact of digital games eliciting explicit and implicit learning processes in preschoolers

Annie Vinter [*,1], Patrick Bard [1], Helle Lukowski-Duplessy [2], Bénédicte Poulin-Charronnat [1]

LEAD - CNRS UMR5022, Université de Bourgogne, France

ARTICLE INFO

Article history:
Received 13 December 2021
Received in revised form 3 August 2022
Accepted 17 August 2022
Available online 27 August 2022

Keywords:
Digital educational games
Impact of learning
Explicit and implicit processes
Early years education
Letter-name knowledge

ABSTRACT

In order to design age-appropriate digital games, it is necessary to make better use of our existing knowledge about learning processes and adopt a true developmental perspective, as the impact of digital games can vary depending on the evolution of the child's cognitive resources with age. The present study compared the impact of digital games that primarily elicit either explicit or implicit learning processes on the acquisition of uppercase letter names in preschoolers aged 3 to 5 years. During a 6-week play session, 144 children were invited to play with implicit or explicit learning-based games run on digital tablets at school individually during their free periods. Their knowledge of letter names, as well as that of the control group, was assessed before and after the play session. The results revealed that the implicit games were more effective than the explicit games and the control condition at ages 3 and 4. In contrast, the 5-year-olds' knowledge of uppercase letter names improved the most with the explicit games when compared to the control group. Most importantly, this study illustrates the interest of studying the effectiveness of digital games by considering the cognitive processes they mobilize and the learner's level of development.

1. Introduction

The main motivation for this study was to open up hitherto little-explored avenues of research in order to improve the construction of effective digital educational games. To design age-appropriate digital games, it seems necessary to make better use of existing knowledge about learning processes and to adopt a true developmental perspective, because the impact of digital games can vary depending on the evolution of the child's cognitive resources with age.

Educational tools have evolved considerably with the advent of the digital age and innovative digital tools have emerged over the last three decades. Teachers and researchers are now increasingly recognizing that digital games are worth exploring for learning purposes (e.g., Kim, Park, & Baek, 2009; Schöbel, Saqr, & Janson, 2021). Play, particularly using digital media, appears ideal for enhancing learning processes (e.g., Prensky, 2001) as well as for promoting motivation (Huang, Huang, & Tschopp, 2010; Papastergiou, 2009; see however Wouters, van Nimwegen, van Oostendorp, & van der Spek, 2013), interest in learning (Iten & Petko, 2016) and learning confidence (Huang, Huang, & Wu, 2014). The idea that play is one of the fundamental activities through which children learn and discover the properties of the world around them has been well established among developmental psychologists for over 50 years (e.g., Piaget and Inhelder (1945) and Vygotsky, 1978). In addition, in a world awash in digital technologies and where children have been described as true 'digital natives' (Prensky, 2001), digital games are highly appealing from an early age, whether they are run on tablets, computers, smartphones, or other digital platforms. Teachers and game designers alike quickly caught onto the idea of exploiting this attractive digital technology for educational purposes, with the result that a wide variety of educational digital games are now available (e.g., Blumberg, 2014). It has indeed proved very tempting to take advantage of the appeal that digital games hold for children and to use them for both pedagogical and remedial purposes (e.g., Pandian, Jain, Raza, & Sahu, 2021; Ronimus, Eklund, Pesu, & Lyytinen, 2019; Saine, Lerkkanen, Ahonen, Tolvanen, & Lyytinen, 2010). Despite some initial reluctance on the part of teachers (Wastiau, Kearney, & Van den Berghe, 2009), the integration of digital games into classroom instruction has increased over the past decade (Dubé & Dubé, 2020).

* Correspondence to: LEAD - CNRS UMR5022, Université de Bourgogne, Pôle AAFE, 11 Esplanade Erasme, 21000 Dijon, France.

E-mail addresses: annie.vinter@u-bourgogne.fr (A. Vinter), patrick.bard@u-bourgogne.fr (P. Bard), hedu@psy.ku.dk (H. Lukowski-Duplessy), benedicte.charronnat@u-bourgogne.fr (B. Poulin-Charronnat).

[1] Annie Vinter, Patrick Bard, and Bénédicte Poulin-Charronnat: LEAD - CNRS UMR5022, Université de Bourgogne, Pôle AAFE, 11 Esplanade Erasme, 21000 Dijon, France.

[2] Now at the Centre for Early Childhood Cognition, Institut for Psykologi, Københavns Universitet, Øster Farimagsgade 2A, 1353 Kbh K.

https://doi.org/10.1016/j.ijcci.2022.100534
2212-8689/

Of course, if the effectiveness of digital games in terms of learning outcomes can be clearly demonstrated, this should also contribute greatly to their acceptance by teachers. A large body of research has been devoted to this issue and has primarily compared the impact of digital game-based learning with that of traditional classroom instruction. In short, numerous studies have indicated that participants learn equally well when taught with digital games or in a traditional learning environment, a great number have concluded in favor of digital games and only a few in favor of conventional instruction (Acquah & Katz, 2020; Fadda, Pelligrini, Vivanet, & Callegher, 2021; Furio, Gonzalez-Gancedo, Juan, Segui, & Rando, 2012; Rachels & Rockinson-Szapkiw, 2017; Tsai & Tsai, 2018). These results encourage us to propose lines of research that can help fine-tune the design of digital educational games.

1.1. Two lines of inquiry

A first line of research focuses on the concept of learning. Digital education should not be reduced to a strategy of digitizing the educational methodology of the past. Along with digitization, there is, as stressed by Hirsh-Pasek et al. (2015), a need to exploit existing knowledge about learning processes in order to better support children's education (see also Brom, Sisler, & Slavik, 2010; Papadakis, Vaiopoulou, Kalogiannakis, & Stamovlasis, 2020) and, indeed, a number of studies have adopted this approach. For example, Elimelech and Aram (2020) developed a digital game aimed at promoting early literacy skills based on Paivio's dual-coding theory (see also Furio et al., 2012; Kyle, Kujala, Richardson, Lyytinen, & Goswami, 2013). The main aim of the present quasi-experiment, which compared the impact of digital games eliciting different learning processes, was to underpin the approach to game development with knowledge from the field of the learning sciences. Most digital game-based learning applications place the learners in meaningful contexts where they are invited to develop hypotheses. They then test these hypotheses, inevitably making errors that generate feedback, and consequently improve them (Van der Graaf, Segers, & Verhoeven, 2016; Van Eck, 2006). The learning processes underlying this type of digital game are explicit and intentional and are demanding in terms of mental effort and working memory (Stadler, 1997). Their aim is to develop explicit knowledge that learners can express verbally (e.g., Verbruggen, Depaepe, & Torbeyns, 2021; Wu, Zhang, & Wang, 2020; Xu, Chen, Eustler, & Geng, 2020). Most of the educational apps for preschoolers available in Apple's app store, for example, rely on an explicit learning strategy, albeit one that primarily takes the form of "drill-and-practice" (Papadakis, Kalogiannakis, & Zaranis, 2018). However, learning can also be supported by non-intentional automatic processes such as those involved in implicit learning. Despite divergencies concerning the mechanisms involved, it is commonly accepted that implicit learning covers all forms of spontaneous and effortless learning which are automatically elicited during the continuous interactions that occur between individuals and their structured environment. Through these interactions, individuals unconsciously acquire relevant information about the world around them without intending to learn anything about it (e.g., Cleeremans, 1993; Perruchet, 2008; Reber, 1993). A few studies have shown that implicit learning does indeed occur during gaming sessions (see Asbell-Clarke & Rowe, 2014; Cadavid, Quijano, Tenorio, & Rosas, 2014; Rowe, Asbell-Clarke, & Baker, 2015; Rowe et al., 2017). By way of example, Rosas et al. (2003) designed video games for the incidental teaching of reading comprehension, spelling and basic math skills to first and second grade children. Their results revealed a significant positive impact of these games, but no comparison with explicit games was performed in this study.

A second way to improve the design of digital games, which is not commonly used in practice, lies in adopting a genuine developmental perspective (Ivory & Ivory, 2017). It is not only important that child-computer interaction analyses cover all developmental periods (Flynn, Kleinknecht, Ricker, & Blumberg, 2021). It may also be equally important to differentiate between age groups at a finer level, as is usually the case in developmental psychology. Indeed, depending on how they are designed, digital games can have a different impact at different ages because of the drastic changes in children's cognitive resources with age. Reich and Black (2012) have sought to make designers of educational virtual environments aware of the need to take account of children's existing and emerging cognitive and social capacities. More specifically, they analyzed the cognitive and social prerequisites that the Webkinz virtual platform considers necessary if users are to succeed in the various games and educational tools it offers. They identified overly high requirements in terms of categorization skills and the understanding of higher-order class-inclusion properties for elementary school children, i.e. the platform's target audience, and this to some extent compromises the intended goal of advancing children cognitively and socially. Similarly, Callaghan and Reich (2020) emphasized, among other issues, the importance of considering young children's limited attentional capacity (e.g., Plude, Enns, & Brodeur, 1994) when creating visual stimuli in educational digital games. These stimuli can quickly become too attractive on their own, possibly preventing children from learning.

Our theoretical framework combines these two lines of research.

1.2. Theoretical framework

In the theoretical framework underpinning the present study, implicit and explicit learning processes are conceived of as being radically different. According to the Self-Organizing Consciousness model (Perruchet & Vinter, 2002, 2021), the former consist in associative learning processes that are mandatorily elicited whenever multiple stimuli or events simultaneously enter the participants' attentional focus, binding them together to create a new cognitive unit. The more frequently these stimuli co-occur, the more fluidly the newly built cognitive unit will guide the participants' perception of the learning situation, feeding their phenomenological experiences. The explicit learning processes are elicited whenever intention and/or explicit instructions guide learning, memory storage, and retrieval. They can be associative (e.g., learning by rote), but mostly involve more sophisticated mental operations like hypothesis-testing. Executive functions, and working memory in particular, constitute significant constraints for explicit learning.

At the developmental level (see e.g., Perruchet & Vinter, 1998), implicit learning processes emerge earlier than explicit processes. They capture the regularities present in the environment that children can attentively process, thus slowly building a knowledge base that increasingly familiarizes them with the world around them. We therefore expected educational games based on implicit learning processes to be the more efficient type of game at the beginning of any new learning phase. However, when sufficient underlying knowledge or an adequate feeling of familiarity with the learning situation has been acquired, hence making the situation immediately meaningful for children, explicit processes oriented by clear instructions are likely to become the more efficient learning processes because learners intentionally recruit all their cognitive resources. In this second developmental step, we therefore expected better performance with explicit educational games than with implicit games. Because working memory, which greatly limits explicit learning, evolves rapidly in the age period of interest in our study, i.e. between 3–4 and 5–6 years of age (Cowan et al., 2005; Pailian, Melissa Libertus, Feigenson, & Halberda, 2016; Simmering, 2012), we decided to compare the respective benefits of games based on explicit and implicit learning processes in preschoolers. These subjects were divided into three age groups on a year-by-year basis, as is usually the case in developmental psychology.

At the level of learning content, the present experiment focused on letter-name knowledge (LNK), i.e., the ability to associate visual information (the letter shape) with auditory information (the letter name). LNK is, of course a basic literacy skill. However, this should not be viewed negatively as seems to be the case in the analysis by Papadakis et al. (2018), who favor more comprehensive educational applications that incorporate typical explicit information processes such as problem-solving or creative thinking. It is, however, crucial that children develop such basic skills before learning to read and LNK is widely recognized across different languages as a major predictor of the successful development of later and more complex literacy skills (McBride-Chang, 1999; Treiman & Kessler, 2003).

The literature shows that both explicit and implicit learning processes contribute to literacy development (Gombert, 2003; Treiman, 1993; Zhang & Treiman, 2021). Labat et al. (2020) reported that 5-year-olds discriminated grapho-phonemic correspondences better in an implicit learning task, but no comparison with an explicit learning approach was undertaken in this study. Regarding existing educational digital games, GraphoGame (or GraphoLearn, Lyytinen, Semrud-Clikeman, Li, Pugh, & Richardson, 2021; Saine et al., 2010) aims to train children to associate auditory utterances (e.g., phonemes, syllables) with their visual correspondences (connections between spoken and written units of different sizes) using only explicit learning processes. Although these games have been shown to be effective in promoting letter-sound knowledge in young children (Bempt et al., 2021), their impact has not been compared to similar games that mobilize implicit learning processes.

1.3. Rationale and research questions

Thus, our goal was *not* to create new educational digital games for preschoolers, but to test the effect of different learning processes on children of different ages. Our purpose in doing so was to help designers of educational game applications identify the most appropriate processes to mobilize depending on the target audience and skills to be learned. More specifically, the challenge was to estimate the potential interest of learning through implicit games, since such games would constitute an innovative new addition to the current wide offer of educational digital games for preschoolers.

To promote acceptance by teachers and parents, the educational content of such games and the intended learning outcomes must be clearly identified (Parker, Thomsen, & Berry, 2022), they must dovetail smoothly with the educational curriculum, and they must be child-friendly (e.g., Walker, 2010). The games must also be evaluated in the light of objective pedagogical criteria. Too many digital games have simply been self-proclaimed as "educational" (Hirsh-Pasek et al., 2015), while a rational evaluation has revealed that most of them do not meet children's needs (Papadakis, Kalogiannakis, & Zaranis, 2017; Papadakis et al., 2018). The present study fulfills these requirements.

To our knowledge, the existing literature does not address the question of the differential impact of educational games involving explicit or implicit learning processes on promoting early literacy skills in preschoolers. It should be noted that the present study focused on LNK and not letter-sound knowledge, as was the case in the above-mentioned studies.

Two research questions (RQs) were therefore addressed in the present study.
RQ1: Can implicit and explicit educational games stimulate LNK in preschoolers compared to a no-game control condition?
RQ2: Is an age-related difference in the impact of explicit or implicit educational games on LNK observable between the ages of 3–4 and 5–6 years?

2. Method

2.1. Participants

One hundred forty-four kindergarten children were enrolled in the experiment. They were divided into three groups: first-grade kindergarteners ($n = 47$, 25 girls and 22 boys, mean age of 3.4 years, hereafter the 3-year-old group), second-grade kindergarteners ($n = 52$, 25 girls and 27 boys, mean age of 4.6 years, hereafter the 4-year-old group) and third-grade kindergarteners ($n = 45$, 22 girls and 23 boys, mean age of 5.6 years, hereafter the 5-year-old group). The recruited kindergarten schools were located in middle-class peri-urban districts. In each group and classroom, some of the children played with explicit games (for the 3-, 4- and 5-year-old group, $n = 20$, $n = 19$ and $n = 17$, respectively), the others with implicit games ($n = 18$, $n = 23$ and $n = 17$, respectively). The remaining thirty children ($n = 9$, $n = 10$ and $n = 11$, respectively) did not play with the games and formed a control group. Thus, within each class, children were randomly assigned to the explicit or implicit game groups or were enrolled in the control group.

None of the children were educationally advanced or retarded, and their vision was normal or corrected to normal. All were native French speakers, although 15 of the 144 children came from families who spoke a language other than French at home. The children played with the digital games in their classroom and were tested individually before and after the gaming session.

This study was conducted in accordance with the ethical standards set out in the 1964 Declaration of Helsinki, and written parental consent was obtained for each participating child (six parental refusals were received because of the use of digital devices). The parental consent letter specified the maximal duration of interaction with the digital games (not longer than 15 min) as well as the number of times per week that they would be accessible to the child (not more than twice a week). At the same time as they were asked to consent to their child's participation, the parents were also asked not to attempt to teach their child the names of the letters during the gaming period. Furthermore, even when parental consent was given, only willing children participated in the study and they were never obliged to do so. The study was approved by a local ethics committee (No. UBFC2021-03-30-002).

2.2. Material

All the games were run on digital Samsung Galaxy Note 10.1 tablets, as preschoolers can handle these devices relatively easily (Hirsh-Pasek et al., 2015). Three implicit and three explicit games were installed on the tablets. To design the implicit games, we inserted learning content into pre-existing recreational games so that implicit learning processes were automatically elicited. For those based on explicit learning, we adapted existing commercial games so that they focused specifically on LNK. A variety of games were accessible to the children in order to keep them as attentive and motivated as possible to play with the tablets during the gaming phase. To make it possible to record individual data, the children's photographs and names were uploaded onto the tablets, and each child had to press his/her own photograph to start playing. The number of times they were exposed to each letter-name association during the games was recorded. Four tablets were available in each classroom.

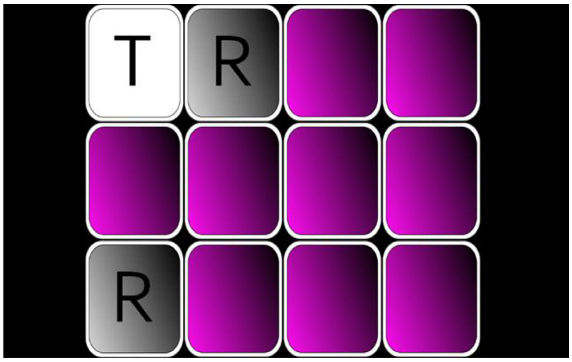

Fig. 1. Illustration of the implicit Memory game.

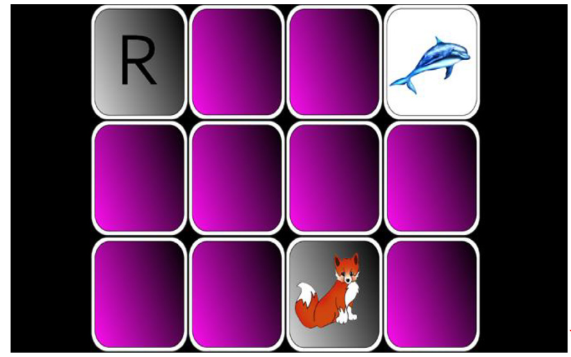

Fig. 2. Illustration of the explicit Memory game.

2.2.1. Implicit games

We adapted commercially available children's games (Memory game, Simon game, Tic-Tac-Toe game) to ensure that they promoted the automatic elicitation of associative implicit learning processes during the normal progress of play. To this end, we followed the advice of Vinter, Pacton, Witt, and Perruchet (2010) who defined four main structural features that any implicit learning situation should provide: no exposure to errors, saliency of the learning material, repetition of the to-be-learned content, and no explicit attention to the material to be learned, meaning that there was also no feedback (see also Vinter & Perruchet, 1999). The implicit games consisted of the incidental teaching of an association between the visual image of an uppercase letter and its name (auditory stimulus) while the participant was playing. In none of them did success in the game or the instructions given to the children require them to learn the letter-name associations.

2.2.1.1. The implicit memory game (see Fig. 1). The objective of the game was to find pairs of identical cards. To do this, the children had to touch two cards in succession among 12 or 28 cards displayed in a grid (of 4 × 3 as in Fig. 1, or of 7 × 4). When a card was touched, a letter (visual stimulus) appeared together with its name (auditory stimulus) and it became white (e.g., T in Fig. 1). When two identical letters were uncovered, they became gray and inactive (e.g., R in Fig. 1). The children were successful if they discovered the positions of two identical cards in the same sequence. To succeed in this game, the children had to match visual shapes, i.e., cards with identical letters, and memorize their positions, but never to learn the association between each letter and its name.

2.2.1.2. The tic-tac-toe game. The objective of the game was to place three identical cards (letters) vertically, horizontally, or diagonally in a 3 × 3 grid. When the child touched a card in the grid, a letter (visual stimulus) was revealed and its name (auditory stimulus) was simultaneously spoken aloud.

2.2.1.3. The simon game. . The player was asked to reproduce an increasingly long sequence of illuminated positions by pressing buttons. Each time a button was pressed, a letter (visual stimulus) appeared, and its name (auditory stimulus) was simultaneously spoken aloud. The participants were successful as long as they reproduced the sequence of illuminated locations correctly (their attention was never drawn to the letters or to the letter-name associations).

2.2.2. Explicit games

The explicit games were inspired by educational games available on the digital game market (e.g., "ABC Rigolo" by Hachette). In all of them (see Fig. 2), the children's attention was explicitly drawn to the letter shape-letter name associations. More precisely, mimicking a teaching procedure used in school, these games aimed to teach associations between a letter (visual and auditory presentation) and a word beginning with that letter (visual and auditory presentation). The children were explicitly asked to memorize the letter shape-letter name association in order to succeed in the game. Immediate feedback was always given, indicating whether the responses were correct or incorrect. Overall, the explicit games were more complex than the implicit games and we will take this factor into account when comparing their respective impacts.

2.2.2.1. The explicit memory game. (see Fig. 2). The goal was to find the correct pairs formed by the visual image of a letter (e.g., R in Fig. 2) and the visual image of an object whose name begins with this letter (e.g., "renard"/fox in Fig. 2). For example, if the children turned over a card with a letter (e.g., R) or a picture (e.g., "renard"/fox), they heard either the corresponding letter name [Er] or the name of the depicted object [r9nAr] (fox) and then had to find the corresponding card, i.e., either the visual image of a fox or the printed R-card. When a card was turned over, it became white (e.g., "dolphin" in Fig. 2). When two cards forming a correct pair were uncovered, they became gray and inactive (i.e., R and 'fox').

2.2.2.2. The association game. . When the children selected a letter, that letter, its name, and a word beginning with that letter (e.g., oral input "*S* of snake") were presented twice together with a picture illustrating the word (e.g., a representation of a snake). First, the children were asked to match the letter with the correct picture (e.g., "slide the *S* onto the snake") among four possible candidates. They then had to indicate the illustration of this letter (visual stimulus) among several different candidates in response to its name (e.g., "touch the *S*"). Finally, the reverse association was asked for (e.g., "slide the snake onto the *S*") and four possible candidate letters were again presented.

2.2.2.3. The lotto game. Each child had a 2 × 3 grid with six cards. In one version of the game, the six cards were pictures. A letter, its name and a word beginning with that letter were presented (e.g., "*S* of snake"), and the child had to drag the letter onto the corresponding picture (among six candidates). In a second version of the game, the six cards were letters and on hearing the letter name (e.g., "*S* of snake"), the child had to drag the picture onto the corresponding letter.

The material used for testing the children before and after the gaming session consisted of 26 small cards of 3 × 3 cm, each with a centered uppercase letter printed on it in black.

2.3. Procedure

2.3.1. Pretest/posttest

The children's LNK of the 26 letters of the alphabet was tested individually before and after the gaming phase. The pretest took place at the beginning of the first term of the school year, and the posttest during the second term, just before the teaching of uppercase letter name began in the second grade of kindergarten. It was therefore only for children in the third grade of kindergarten that our intervention was accompanied by systematic explicit teaching in class.

The cards were presented in a random order. The experimenter showed a card with a printed letter to the child and asked: "Do you know the name of this letter? Can you tell me its name?" The child's response was recorded and coded as correct or false. A different order was used for each child and each phase (pretest/posttest).

2.3.2. Familiarization phase

The experimenter, accompanied by the teacher, showed the children how to use the tablets (in particular, how to access their own names/photographs) and how to run the games they had access to. This demonstration phase lasted around 20 min and was given in small groups of four to six children of the same age and assigned to the same experimental group. The teacher and the classroom assistants remained available during the entire gaming period to help any children who encountered difficulties in using the tablets. Most of the 4 to 5-year-olds had already used digital tablets, either to watch cartoons or to play games. The younger children were familiar with this type of equipment even though most of them did not know how to use it. However, after a demonstration and additional help during the first two gaming weeks, they quickly became autonomous in their interactions with the tablets.

2.3.3. Gaming phase

The children had access to the tablets during their free periods at school. In each class, 2 tablets were always allocated to children playing explicit games and the other 2 to those playing implicit games, so that the overall duration of play time was similar in the two conditions. The children were strongly encouraged to play, but they were not obliged to. Consequently, some of them played very often and others much less frequently. Additionally, depending on the total number of times the children ran the games, they could be exposed to a larger or smaller subsection of the alphabet. It should also be noted that, due to their design, the explicit games took longer presenting each letter-name association (see, for example, the association game) than the implicit games, in which the associations followed one another rapidly (see, for example, the Simon game). Every time the children played a game, a random selection of letter-name associations was presented. They played individually and were equipped with a headphone to reduce potential disturbances in the playing room due to the simultaneous presence of other players. Informal reports from the teachers and assistants indicated that in both learning conditions, children preferred playing with the Memory game, with which they were familiar.

The gaming period lasted 6 weeks.

2.4. Data analysis

We first checked whether the children played with the tablets for a reasonable amount of time. Thirteen did not play at all and seventeen played so infrequently that they experienced less than two repetitions of each letter-name association encountered over the entire gaming session. They served as control children, attending the same classes as those who played with the explicit or implicit games, with 9 children at age 3, 10 at age 4 and 11 at age 5, thus controlling for the potential effects of the teachers' instructions in the classroom. Although this control group was clearly not "ideal", the idea of setting up an a priori control group was not acceptable to the teachers and a between-subject design for the control group also had obvious shortcomings due to a potential teacher effect. This forced us to be cautious when comparing the performances of the groups, as children were not randomly assigned to the control group in the way that they were to the other two groups.

The pretest and posttest assessed the children's LNK on the full alphabet in the three groups (explicit/implicit/control). Six children displayed ceiling performance in the pretest, naming all 26 letters correctly. Their data were excluded from the analyses (the initial sample included 150 children). Concerning the gaming phase, the proportions of to-be-learned associations the children encountered and the mean number of repetitions of these associations were computed for the children assigned to the explicit or implicit game group by merging the data across the games over the gaming session. Two learning gain scores were computed: an absolute gain score (the percentage of LNK in posttest minus the percentage of LNK in pretest) and a relative gain score (N-gain score, Hake (1998)) that considers the change between pretest and posttest in the light of the child's remaining LNK progression margin, measured on the basis of the level of prior knowledge in the pretest (absolute gain divided by 100% minus the percentage of LNK at pretest). When computing these scores, we excluded five letters (C, G, H, W, and Y) whose names and sounds are only weakly related in French. The number of letter-name associations to be learned was therefore 21. The distribution of the learning gain scores did not deviate significantly from normality (Shapiro–Wilk test, $p > .50$). Univariate ANOVAs with Group (explicit/implicit/control) or Games (explicit/implicit) and Age (3 years/4 years/5 years) as between-subject factors were run on the different variables.

3. Results

We first checked that the proportions of the 21 to-be-learned letter-name associations encountered during the game (control group excluded), as well as their mean number of repetitions, were high enough to allow a comparative analysis of the impact of the two game categories. Fig. 3 presents these results as a function of Game and Age.

Fig. 3 A shows that the children were exposed to a very large proportion of the 21 associations to be learned (around 90% on average). However, the ANOVA revealed a significant Game effect, $F(1, 108) = 4$, $p = .049$, $\eta_p^2 = .036$, with a larger proportion seen by children playing with the implicit ($M = 95.1\%$, $SD = 13.2\%$) rather than the explicit games ($M = 89\%$, $SD = 17\%$), although the significant interaction between Game and Age indicated that this Game effect was present mainly at 3 years of age, $F(2, 108) = 3.5$, $p = .034$, $\eta_p^2 = .06$. Fig. 3B shows that, on average, the children who played with the implicit games encountered each association around three times more often ($M = 37.8$, $SD = 26.4$) than those who played with the explicit games ($M = 12.1$, $SD = 6.8$), $F(1, 108) = 504$, $p < .001$, $\eta_p^2 = .32$. The Age effect was significant, $F(2, 108) = 5.9$ $p = .004$, $\eta_p^2 = .098$, with the greatest exposure to the associations to be learned being observed at age 4. Moreover, as indicated by the significant Game × Age interaction, $F(2, 108) = 4.6$, $p = .012$, $\eta_p^2 = .079$, the advantage of the implicit games in terms of exposure to the associations to be learned was much less consistently observed at age 5 than at the younger ages.

Before comparing the performance of the children assigned to each of the three groups, we verified that these groups did not differ from each other with respect to their initial level of LNK assessed in the pretest. T-tests showed that none of the comparisons proved to be significant, $p_s > .23$. The effect of gaming was examined by carrying out univariate ANOVAs with Group

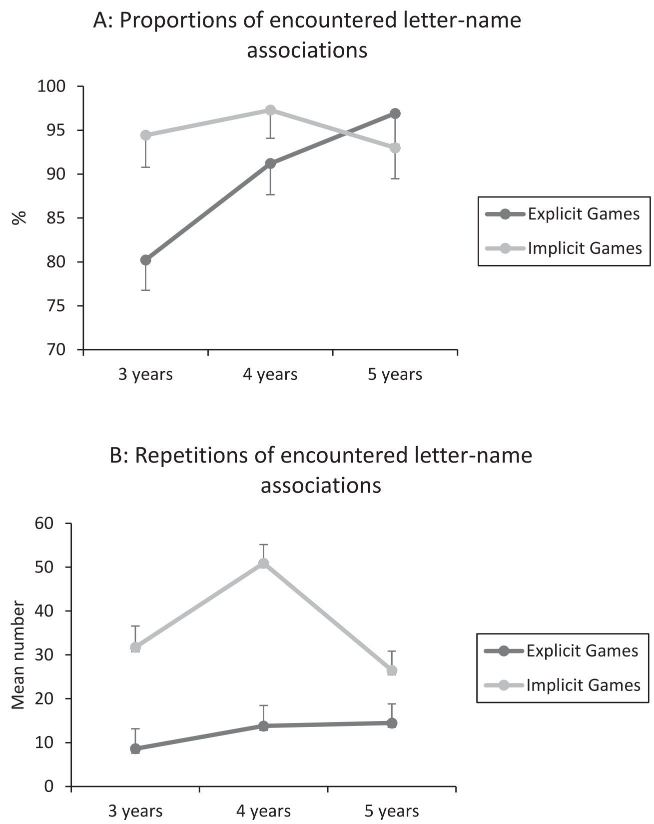

Fig. 3. Proportions and mean number of repetitions of encountered letter-name associations. Percentages of encountered letter-name associations to be learned (Fig. 3 A) and mean number of repetitions of encountered letter-name associations (Fig. 3B) as a function of Game and Age. Error bars indicate standard errors.

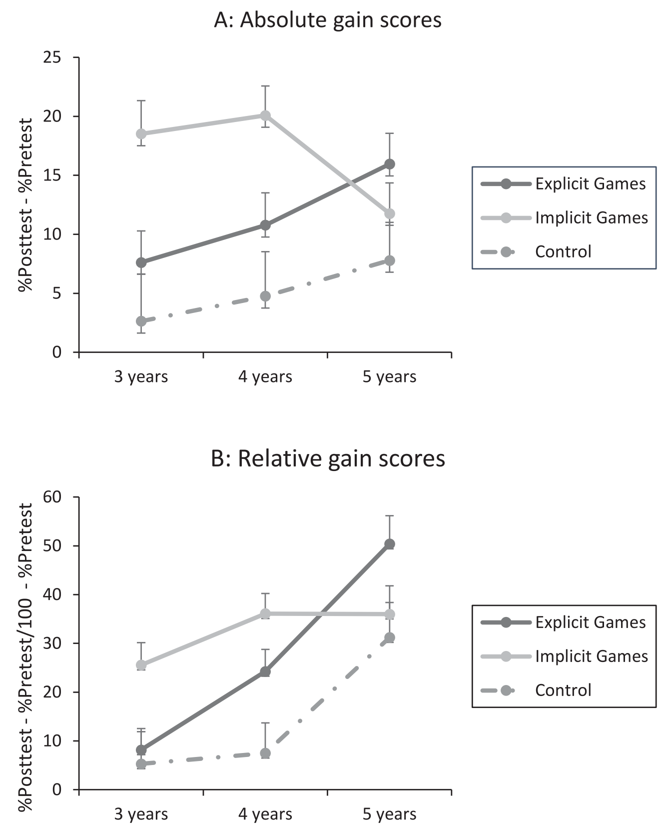

Fig. 4. Learning gain scores. Learning gain scores (A: Absolute gain scores; B: Relative gain scores) as a function of Group and Age. Error bars show standard errors.

(explicit/implicit/control) and Age (3 years/4 years/5 years) as between-subject factors on the two learning gain scores, followed by post hoc comparisons using Bonferroni corrections. The results are illustrated in Fig. 4 (4A: Absolute gain scores; 4B: Relative gain scores).

The ANOVA run with the absolute gain scores revealed a significant Group effect, $F(2, 135) = 11.9$, $p < .001$, $\eta_p^2 = .15$. As illustrated in Fig. 4A and confirmed by Scheffé post hoc comparisons, the gaming effect was stronger with the implicit games than with the explicit games or in the control group, $p_s < .01$, and stronger with the explicit games than in the control group, $p = .05$. Age was not significant, $F(2, 135) < 1$, but there was a significant interaction between Group and Age, $F(4, 135) = 2.89$, $p = .025$, $\eta_p^2 = .079$. The children in the implicit games group outperformed those in the explicit games group at 3 and 4 years of age, but not at 5 years of age, $p = .13$. Similarly, the performance of the children playing with the implicit games was better than that of the control group at age 3 and age 4, but not at age 5, $p = .17$. The analysis of the relative gain scores confirmed that the children in the implicit games group made more progress than those in the other conditions, $F(2, 135) = 5.59$, $p = .005$, $\eta_p^2 = .077$. These scores improved significantly with age, particularly with the explicit games, $F(2, 135) = 13.2$, $p < .001$, $\eta_p^2 = .16$. The significant Age by Group interaction, $F(4, 135) = 2.55$, $p = .042$, $\eta_p^2 = .07$, indicated that at age 5, the children playing the explicit games outperformed those in the control group, $p = .05$, whereas this difference was not significant at age 3, $p = .71$. Conversely,q the children playing with the implicit games outperformed those in the control group at age 3, $p < .05$, whereas this difference did not reach significance at age 5, $p = .48$. It is worth noting that at age 3, playing with the implicit games also led to better relative learning gain scores than were observed in the explicit games group, $p < .05$.

4. Discussion

Studies going back several decades have demonstrated the positive role that digital learning games can play in child and adult development (e.g., Iten & Petko, 2016; Mayer, Parong, & Baindridge, 2019; McFarlane, Sparrowhawk, & Heald, 2002). A wide variety of academic subjects (e.g., mathematics, physics, literacy, second language) as well as more societally-oriented topics (economy, sustainable development, ecology, handicap and so on…) or general cognitive functions (e.g., executive functions) have provided material for the creation of digital games. It is now worth studying how to improve digital game-based learning by exploring the impact of eliciting different learning processes when designing these games (Wang & Chen, 2010) or by adopting a developmental perspective to test their effect at different ages (Acquah & Katz, 2020). Pursuing these lines of research, two main research questions guided the present experiment, one being whether implicit and explicit educational digital games can stimulate LNK in preschoolers, and the other asking whether these two categories of games can have a different impact depending on the age of the child. To answer these questions, the study compared the impact of digital games that primarily elicit either explicit or implicit learning processes on LNK acquisition in preschoolers aged 3 to 5 years. The effectiveness of implicit and explicit learning games was tested in children attending the same classes, so that the simultaneous influence of literacy activities at school was the same in the two groups. In addition, comparisons were also made with control children drawn from the same classes.

It is worth noting that, from an early age, the children showed themselves capable of using our digital games autonomously, as teachers expect from educational applications (Rosas et al., 2003). The children genuinely enjoyed the games, as indicated by the large number of repetitions of the letter-name associations they were confronted with. Given that we adapted well-known recreational games (Memory, Simon game) to construct the implicit games, the "tension" between play and learning (Brom et al., 2010) could have been detrimental to learning with these games, with the excitement of the game taking precedence over the attention needed for any learning. This was not the case and the children learned incidentally while playing. This result is a major contribution to the field as it could help open up a promising avenue for the design of innovative educational apps. However, the study also revealed important findings regarding these implicit games when compared to explicit games.

On the one hand, both implicit learning-based games and explicit learning-based games had an effective impact on children's LNK compared to the control condition, showing that when implicit learning processes are properly implemented, even recreational games can indeed contribute to children's learning (RQ1). On the other, implicit learning-based games were found to be more effective than explicit learning-based games at ages 3 and 4, but not at age 5, with 5-year-olds' LNK improving the most with explicit learning-based games compared to the control group. This shows that the impact of digital games may well vary across ages depending on the learning processes they primarily engage (RQ2).

Several explanations, which are not mutually exclusive, can be put forward to account for these results. The explicit games were necessarily more demanding in terms of working memory requirements and were cognitively more complex than the implicit games, which focused on simpler perceptual processes (matching visual shapes). This may explain why younger children aged 3 and 4 years, with poorly developed executive function skills (e.g., Swanson, 2017), did better with the less cognitively demanding implicit games. Verbruggen et al. (2020) pointed out that the limited cognitive resources of young children can affect the effectiveness of digital learning games when, for example, understanding instructions or manipulating the games places an excessive load on children's capabilities.

Another explanation, which emphasizes the role of prior knowledge, could be added to this account. With reference to the theoretical model adopted here (Perruchet & Vinter, 2002), it could be suggested that a learning method based on implicit processes will be more effective during the first phase of any learning, when learners are still completely new to the skill to be acquired. Reber (1993) demonstrated that implicit learning processes are more effective than explicit ones in complex learning tasks. A task appears all the more difficult, and therefore complex, to learners while they are still novices with a low level of prior knowledge. In our study, 3-year-olds knew on average only 3 uppercase letters before beginning game-based learning, whereas 5-year-olds knew 14 letters. Implicit learning processes help to generate a progressive feeling of familiarity with the learning situation (Servan-Schreiber & Anderson, 1990) by modifying the learner's subjective phenomenological experience and the way the learning situation is perceived (Perruchet & Vinter, 2002). It is likely that when the initial level of LNK is far from negligible (as was the case at age 5), hence making the situation meaningful to them, children immediately perceive an unknown letter-name association as "novel", thereby prompting learning. The explicit gaming condition would be better able to appropriately mobilize children's attention and the cognitive abilities necessary to memorize the not yet known association.

Finally, one further explanation might account for the significant differences observed between the frequencies with which children are exposed to the associations to be learned in implicit and explicit games. Frequency-based learning effects are generally observed in both explicit and implicit learning conditions (for language learning, see, e.g., Hamrick & Rebuschat, 2014; Kidd, Lieven, & Tomasello, 2006; for a frequency-based account of implicit learning, see, e.g., Johnstone & Shanks, 2001; Perruchet, 2008). A large body of research has shown that associative mechanisms cause high-frequency patterns, whether auditory or visual, to be learned better than low-frequency ones in both children and adults (e.g., Fiser & Aslin, 2001; Lieven, 2010; Perruchet & Pacteau, 1990; Saffran, 2003). Children who played with the implicit games encountered more letter-name repetitions, and this difference could account for the greater learning gains in the children who played with these games at ages 3 and 4. By age 5, the difference in the frequency of letter-name associations encountered between the two gaming conditions was much less pronounced, and those additionally presented in school during letter-name teaching may have been sufficient to cause a reversal of impact between implicit and explicit games, with a slight advantage in favor of the latter being observed at this age. It is worth noting that the 5-year-olds who played with the implicit games also received this explicit instruction at school but did not perform as well as their counterparts who played the explicit games after the 6-week training. Regarding the controversial issue of the relative impact of explicit versus implicit learning (e.g., Lichtman, 2016; Maxwell, Capio, & Masters, 2017; Reber, 1993; Sætrevik, Reber, & Sannum, 2006), this finding suggests that subjects who are exposed to both types of learning in parallel do not necessarily benefit from all their respective advantages. This idea echoes (Cornillie, Clarebout, & Desmet, 2012) finding that implicit corrective feedback was not found to be as useful for learning as explicit corrective feedback by students participating in an explicit digital game designed to teach English as a foreign language. With regard to digital technology in education, this result suggests that educational digital games may potentially have a greater impact when they are aligned or consistent with the educational practices followed in school.

5. Limitations of the study

Some methodological weaknesses presented by the present study are worth noting, as they could be rectified in future work. Our aim was to compare the impact of games involving implicit or explicit learning processes for acquisition of one and the same thing, i.e. the names of letters. Explicit games already existed on the market, whereas implicit games did not, meaning that we had to construct them ourselves. It is unfortunate that we were unable to find games that were able to function identically under implicit or explicit learning instructions. However, our intention was to show the importance of taking account of the nature of the learning processes elicited by digital games, not to study in detail the differences between implicit and explicit learning. Another concern is that the control group was made up of children who were not authorized to use the digital tablets by their parents or who chose not to play the games much. They were not, as would have been ideal, randomly assigned to the control condition. Their initial level of LNK did not differ from that of the other children, but there may also have been other differences between the groups that may have interfered with our intervention. However, the age-related development of their absolute or relative learning gains showed that they progressed in LNK as would have been normally expected. The absence of a longitudinal perspective is also regrettable since this would have made it possible to assess whether the young children aged 3–4 years who had benefited from implicit learning subsequently did better than the control children when they were explicitly taught letter names in school. This empirical question deserves to be raised in future work. It would also have been preferable to have a longer play period since this might have modified the comparisons between the effectiveness of implicit or explicit learning-based games. Finally, the main critical point that may limit the generalizability of the results concerns the elementary nature of the learning content implemented in the games. Whether the current results can be applied to more complex learning situations, considered by a number of scientists (Hirsh-Pasek et al., 2015; Papadakis et al., 2017, 2018) to be those of greatest interest for educational applications, remains an open question. Clearly, the scope of implicit processes is limited by their purely associative nature, although they can obviously encompass more complex learning situations than those linking only two simple items, as was the case in the present study.

6. Conclusion and implications

In conclusion, this study confirms the interest of analyzing the impact of digital learning games by differentiating between age groups and learning approaches. More specifically, it has shown the effectiveness of implicit learning games, constructed on the basis of the advice given by Vinter et al. (2010), for young children's basic cognitive acquisitions. This should reassure teachers about the use of digital games in the classroom as a complement to traditional teaching. Moreover, our results should draw teachers' attention to the importance of analyzing the learning processes solicited by the games they might use in class and their appropriateness with regard to the cognitive resources available to the children in their care.

One possible implication of these results for the developers of educational games is that it may be beneficial to design implicit digital games that sensitize very young children, and indeed any novice learners regardless of age, to new learning materials or situations. As already mentioned, implicit learning processes help generate a progressive feeling of familiarity with the learning situation (Servan-Schreiber & Anderson, 1990) by modifying the subjective experience of the learner (Perruchet & Vinter, 2002) and this could facilitate subsequent explicit learning, as shown by Asbell-Clarke and Rowe (2014). The type of implicit game developed in the present study seems particularly suitable for any learning content than can be expressed by the association of two elements, which is the case for a wide variety of acquisitions: for example, vocabulary (in different languages), multiplication tables, musical notes, or even the recognition of facial emotions. It should also be noted that inserting educational content into commercial games that are sure to be attractive to children appears to be an effective strategy. This technology can also easily be adapted to adults, and particularly to elderly individuals (Wang, Hou, & Tsai, 2020), by diversifying and complexifying the games. However, these lines of research deserve to be explored in controlled experimental studies before publishers embark on the development of a new family of educational digital games.

Finally, educational policymakers may also find our approach and findings interesting. We have shown that it is preferable to start learning a new skill using an implicit rather than an explicit method, but that it is then desirable to continue with an explicit method in order to accelerate acquisition. An educational approach consisting of two stages (at least; the present study does not allow us to go any further) could therefore be of value, involving a first phase in which errorless learning (a characteristic of implicit learning) dominates. Furthermore, in terms of supporting education through digital technology, our study confirms the interest of equipping schools with digital tablets that children can use independently during their free time to access simple educational games.

Selection and participation of children

All the children participating in the study were preschoolers from public schools in Dijon, France, located in peri-urban districts. The study took place inside the schools. The digital tablets with the uploaded games were given to the teachers for the children's free times. The pre and post-test were run in a quiet room inside the schools. As mentioned in the ms, informed written parental consent was asked to the children's parents. Children were also free to participate or not to the study. The experiment received agreement from the ethical committee of the university. Children and parents were able to withdraw their consent for the data collection at any time and to stop their participation to the study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors are very grateful to Pierre Perruchet for his highly appreciated comments on earlier versions of the manuscript and to Livia Goldstein, Mélissa Spinola, Léonie Mitaine and Marion Daumas for their contribution to data collecting. They express their most sincere thanks to Timothy Pownall for his careful corrections of the English of the manuscript.

References

Acquah, E. O., & Katz, H. T. (2020). Digital game-based L2 learning outcomes for primary through high-school students: A systematic literature review. *Computers and Education*, *143*, Article 103667. http://dx.doi.org/10.1016/j.compedu.2019.103667.

Asbell-Clarke, J., & Rowe, E. (2014). Scientific inquiry in digital games. In F. Blumberg (Ed.), *Learning by playing: frontiers of video gaming in education* (pp. 246–260). Oxford University Press.

Bempt, F. V., Economou, M., Van Herck, S., Vanderauwera, J., Glatz, T., Vandermosten, M., et al. (2021). Digital game-based phonics instruction promotes print knowledge in pre-readers at cognitive risk for dyslexia. *Frontiers in Psychology*, *12*, Article 720548. http://dx.doi.org/10.3389/fpsyg.2021.720548.

Blumberg, F. C. (2014). *Learning by playing: video gaming in education*. Oxford University Press.

Brom, C., Sisler, V., & Slavik, R. (2010). Implementing digital game-based learning in schools: augmented learning environment of 'Europe 2045'. *Multimedia Systems*, *16*(23), 23–41. http://dx.doi.org/10.1007/s00530-009-0174-0.

Cadavid, N., Quijano, M. C., Tenorio, M., & Rosas, R. (2014). Play as a vehicle for enhancing reading skills in children with poor reading ability. *Pensamiento Psicologico*, *12*(1), 23–38. http://dx.doi.org/10.11144/Javerianacali.PPSI12-1.jvmh.

Callaghan, M. N., & Reich, S. M. (2020). Applying a developmental lens to educational game designs for preschoolers. *International Journal of Mobile and Blended Learning*, *12*(2), 1–15. http://dx.doi.org/10.4018/IJMBL.2020040101.

Cleeremans, A. (1993). *Mechanisms of implicit learning: connectionist models of sequence processing*. The MIT Press.

Cornillie, F., Clarebout, G., & Desmet, P. (2012). Between learning and playing? Exploring learners'perception of corrective feedback in an immersive game for English pragmatics. *Recall*, *24*, 257–278. http://dx.doi.org/10.1017/S09583440120000146.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*, 42–100. http://dx.doi.org/10.1016/j.cogpsych.2004.12.001.

Dubé, A. K., & Dubé, N. J. (2020). Policies to guide the adoption of educational games into classrooms. *Educational Technology Research and Development*, http://dx.doi.org/10.1007/s11423-020-09835-9.

Elimelech, A., & Aram, D. (2020). Using a digital spelling game for promoting alphabetic knowledge of preschoolers: The contribution of auditory and visual supports. *Reading Research Quarterly*, *55*(2), 235–250. http://dx.doi.org/10.1002/rrq.264.

Fadda, D., Pelligrini, M., Vivanet, G., & Callegher, C. Z. (2021). Effects of digital games on student motivation in mathematics: A meta-analysis in K-12. *Journal of Computer Assisted Learning*, 1–22. http://dx.doi.org/10.1111/jcl.12618.

Fiser, J., & Aslin, R. N. (2001). Unsupervised statistical learning of higher-order spatial structures from visual scenes. *Psychological Sciences*, *12*(6), 499–504. http://dx.doi.org/10.1111/1467-9280.00392.

Flynn, R. M., Kleinknecht, E., Ricker, A. A., & Blumberg, F. C. (2021). A narrative review of methods used to examine digital impacts on learning and cognition during middle childhood. *International Journal of Child-Computer Interaction*, *30*, Article 100325. http://dx.doi.org/10.1016/j.ijcci2021.100325.

Furio, D., Gonzalez-Gancedo, S., Juan, M-C., Segui, I., & Rando, N. (2012). Evaluation of learning outcomes using an educational iphone game vs traditional game. *Computers and Education*, *64*, 1–23. http://dx.doi.org/10.1016/j.compedu.2012.12.001.

Gombert, J.-E. (2003). Implicit and explicit learning to read: implication as for subtypes of dyslexia. *Current Psychology Letters*, *10*(1), Special Issue on Language Disorders and Reading Acquisition. http://dx.doi.org/10.4000/cpl.202.

Hake, R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64–74. http://dx.doi.org/10.1119/1.18809.

Hamrick, P., & Rebuschat, P. (2014). Frequency effects, learning conditions, and the development of implicit and explicit lexical knowledge. In J. Connor-Linton, & L. Amoroso (Eds.), *Measured language: quantitative approaches to acquisition, assessment, processing and variation* (pp. 125–139). Georgetown University Press.

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in educational apps: Lessons from the science of learning. *Psychological Science in the Public Interest*, *16*(1), 3–34. http://dx.doi.org/10.1177/1529100615569721.

Huang, Y. M., Huang, S. H., & Tschopp, J. (2010). Sustaining iterative game playing processes in DGBL: The relationship between motivational processing and outcome processing. *Computers and Education*, *55*(2), 789–797. http://dx.doi.org/10.1016/j.compedu.2010.03.011.

Huang, Y. M., Huang, S. H., & Wu, T. T. (2014). Embedding diagnostic mechanisms in a digital game for learning mathematics. *Educational Technology Research and Development*, *62*, 187–207. http://dx.doi.org/10.1007/s11423-013-9315-4.

Iten, N., & Petko, D. (2016). Learning with serious games: Is fun playing the game a predictor of learning success? *British Journal of Educational Technology*, *47*(1), 151–163. http://dx.doi.org/10.1111/bjet.12226.

Ivory, A. H., & Ivory, J. D. (2017). On the need for developmental perspectives in research on the potential positive and negative health effects of digital games. *Mobile E-Health*, 201–214. http://dx.doi.org/10.1007/978-3-319-60672-9.

Johnstone, T., & Shanks, D. (2001). Abstractionist and processing accounts of implicit learning. *Cognitive Psychology*, *42*, 61–112. http://dx.doi.org/10.1006/cogp.2000.0743.

Kidd, E., Lieven, E., & Tomasello, M. (2006). Examining the role of lexical frequency in children's acquisition and processing of sentential complements. *Cognitive Development*, *21*, 93–107. http://dx.doi.org/10.1016/j.cogdev.2006.01.006.

Kim, B., Park, H., & Baek, Y. (2009). Not just fun, but serious strategies: Using meta-cognitive strategies in game-based learning. *Computers and Education*, *52*(4), 800–810. http://dx.doi.org/10.1016/j.compedu.2008.12.004.

Kyle, F., Kujala, J., Richardson, E., Lyytinen, H., & Goswami, U. (2013). Assessing the effectiveness of two theoretically motivated computer-assisted reading intervention in the United Kingdom: GG rime and GG phoneme. *Reading Research Quarterly*, *48*, 61–76. http://dx.doi.org/10.1002/rrq.038.

Labat, H., Boisson, A., Brunel, L., Ecalle, J., Versace, R., & Magnan, A. (2020). Multisensory letter integration and implicit learning of reading with 5-year-old children. *European Review of Applied Psychology*, *70*(1), Article 100477. http://dx.doi.org/10.1016/j.erap.2019.100477.

Lichtman, K. (2016). Age and learning environment: Are children implicit second language learners? *Journal of Child Language*, *43*(3), 1–24. http://dx.doi.org/10.1017/S0305000915000598.

Lieven, E. (2010). Input and first language acquisition: Evaluating the role of frequency. *Lingua*, *120*, 2546–2556.

Lyytinen, H. J., Semrud-Clikeman, M., Li, H., Pugh, K., & Richardson, U. (2021). Supporting acquisition of spelling skills in different orthographies using an empirically validated digital learning environment. *Frontiers in Psychology*, *12*, Article 566220. http://dx.doi.org/10.3389/fpsyg.2021.566220.

Maxwell, J. P., Capio, C. M., & Masters, R. S. W. (2017). Interaction between motor ability and skill learning in children: Application of implicit and explicit approaches. *European Journal of Sport Science*, *17*(4), 407–416. http://dx.doi.org/10.1080/17461139.2016.1268211.

Mayer, R. E., Parong, J., & Baindridge, K. (2019). Young adults learning executive function skills by playing focused video games. *Cognitive Development*, *49*, 43–50. http://dx.doi.org/10.1016/j.cogdev.2018.11.002.

McBride-Chang, C. (1999). The ABCs of the ABCs: The development of letter-name and letter-sound knowledge. *Merrill-Palmer Quarterly*, *45*(2), 285–308.

McFarlane, A., Sparrowhawk, A., & Heald, Y. (2002). Report on the educational use of games: An exploration by TEEM of the contibution which games can make to the education process. (On line). Available: http://reservoir.cent.uji.es/canals/octeto/es/440.

Pailian, H., Melissa Libertus, E., Feigenson, L., & Halberda, J. (2016). Visual working memory capacity increases between ages 3 and 8 years, controlling for gains in attention, perception, and executive control. *Attention, Perception and Psychophysics*, *78*, 1556–1573. http://dx.doi.org/10.3758/s13414-016-1140-5.

Pandian, G. S. D. B., Jain, A., Raza, Q., & Sahu, K. K. (2021). Digital health interventions (DHI) for the treatment of attention deficit hyperactivity disorder (ADHD) in children – a comparative review of literature among various treatment and DHI. *Psychiatry Research*, *297*, Article 113742. http://dx.doi.org/10.1016/j.psyres.2021.113742.

Papadakis, S., Kalogiannakis, M., & Zaranis, N. (2017). Designing and creating an educational app rubric for preschool teachers. *Education and Information Technologies*, *22*, 3147–3165. http://dx.doi.org/10.1007/s10639-017-9579-0.

Papadakis, S., Kalogiannakis, M., & Zaranis, N. (2018). Educational apps from the android Google play for greek preschoolers: A systematic review. *Computers and Education*, *116*, 139–160. http://dx.doi.org/10.1016/j.compedu.2017.09.007.

Papadakis, S., Vaiopoulou, J., Kalogiannakis, M., & Stamovlasis, D. (2020). Developing and exploring an evaluation tool for educational apps (E.T.E.A) targeting kindergarten children. *Sustainability*, *12*, 4201. http://dx.doi.org/10.3390/su12104201.

Papastergiou, M. (2009). Digital game-based learning in high school computer science education: Impact on educational effectiveness and student motivation. *Computers and Education*, *52*(1), 1–12. http://dx.doi.org/10.1016/j.compedu.2008.06.004.

Parker, R., Thomsen, B. S., & Berry, A. (2022). Learning through play at school – A framework for policy and practice. *Frontiers in Education*, *7*, Article 751801. http://dx.doi.org/10.3389/feduc.2022.751801.

Perruchet, P. (2008). Implicit learning. In J. Byrne (Ed.), *Cognitive psychology of memory (Vol. 2): of learning and memory: a comprehensive reference* (pp. 597–621). Elsevier, http://dx.doi.org/10.1016/B978-012370509-9.00149-2.

Perruchet, P., & Pacteau, C. (1990). Synthetic grammar learning: Implicit rule abstraction or explicit fragmentary knowledge. *Journal of Experimental Psychology: General*, *119*(3), 264–275. http://dx.doi.org/10.1037/0096-3445.119.3.264.

Perruchet, P., & Vinter, A. (1998). Learning and development: the implicit knowledge assumption reconsidered. In M. Stadler, & P. Frensch (Eds.), *Handbook of implicit learning* (pp. 495–531). Thousand Oaks: Sage.

Perruchet, P., & Vinter, A. (2002). The self-organizing consciousness. *Behavioral and Brain Sciences*, *25*(3), 297–388. http://dx.doi.org/10.1017/S0140525X02000067.

Perruchet, P., & Vinter, A. (2021). The self-organizing consciousness: Implications for deep learning. *Trends in Artificial Intelligence*, *5*, 87–94. http://dx.doi.org/10.36959/643/307.

Piaget, J., & Inhelder, B. (1945). *La formation du symbole chez l'enfant*. Delachaux et Niestlé.

Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta Psychologica*, *86*, 227–272. http://dx.doi.org/10.1016/0001-6918(94)90004-3.

Prensky, M. (2001). *Digital game-based learning*. McGraw-Hill.

Rachels, J. R., & Rockinson-Szapkiw, A. J. (2017). The effects of a mobile gamification app on elementary students' spanish achievement and self-efficacy. *Computer Assisted Language Learning*, *31*(1(2)), 72–89. http://dx.doi.org/10.1080/09588221.2017.1382536.

Reber, A. S. (1993). *Implicit learning and tacit knowledge: an essay on the cognitive unconscious*. Oxford University Press.

Reich, S. M., & Black, R. W. (2012). Missed opportunities on webkinz when developmental abilities are not considered. *Journal of Applied Developmental Psychology*, *33*, 136–145. http://dx.doi.org/10.1016/j.appdev2012.02.001.

Ronimus, M., Eklund, K., Pesu, L., & Lyytinen, H. (2019). Supporting struggling readers with digital game-based learning. *Education Technology Research Development*, *67*, 639–663. http://dx.doi.org/10.1007/s11423-019-09658-3.

Rosas, R., Nussbaum, M., Cumsille, P., Marianov, V., Correa, M., Flores, P., et al. (2003). Beyond Nintendo: Design and assessment of educational video games for first and second grade students. *Computers and Education*, *40*(1), 71–94. http://dx.doi.org/10.1016/S0360-1315(02)00099-4.

Rowe, E., Asbell-Clarke, J., & Baker, R. S. (2015). Serious games analytics to measure implicit science learning. In C. Loh, Y. Sheng, & D. Ifenthaler (Eds.), *Serious games analytics* (pp. 343–360). Springer International.

Rowe, E., Asbell-Clarke, J., Baker, R. S., Eagle, M., Hicks, A. G., Barnes, T., et al. (2017). Assessing implicit science learning in digital games. *Computers in Human Behavior*, *76*, 617–630.

Sætrevik, B., Reber, R., & Sannum, P. (2006). The utility of implicit learning in the teaching of rules. *Learning and Instruction*, *16*(4), 363–373. http://dx.doi.org/10.1016/j.learninstruc.2006.07.006.

Saffran, J. (2003). Statistical language learning: Mechanisms and constraints. *Current Directions in Psychological Science*, *12*, 110–114.

Saine, N. L., Lerkkanen, M. K., Ahonen, T., Tolvanen, A., & Lyytinen, H. (2010). Computer-assisted remedial reading intervention for school beginners at risk for reading disability. *Child Development*, *82*(3), 1013–1028. http://dx.doi.org/10.1111/j.1467-8624.2011.01580.x.

Schöbel, S., Saqr, M., & Janson, A. (2021). Two decades of game concepts in digital learning environments – A bibliometric study and research agenda. *Computers and Education*, *173*, Article 104296. http://dx.doi.org/10.1016/j.compedu.2021.104296.

Servan-Schreiber, E., & Anderson, J. R. (1990). Learning artificial grammars with competitive chunking. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*(4), 592–608. http://dx.doi.org/10.1037/0278-7393.16.4.592.

Simmering, V. R. (2012). The development of visual working memory capacity during early childhood. *Journal of Experimental Child Psychology*, *111*, 695–707. http://dx.doi.org/10.1016/j.jecp.2011.10.007.

Stadler, M. A. (1997). Distinguishing implicit and explicit learning. *Psychonomic Bulletin and Review*, *4*(1), 56–62. http://dx.doi.org/10.3758/BF03210774.

Swanson, H. L. (2017). Verbal and visual-spatial working memory: What develops over a life span? *Developmental Psychology*, *53*(5), 971–995. http://dx.doi.org/10.1037/dev0000291.

Treiman, R. (1993). *Beginning to spell: a study of first-grade children*. Oxford University Press.

Treiman, R., & Kessler, B. (2003). The role of letter names in the acquisition of literacy. In R. V. Kail (Ed.), *Advances in child development and behavior, Vol 31* (pp. 105–135). Academic Press.

Tsai, Y. L., & Tsai, C. C. (2018). Digital game-based second language vocabulary learning and conditions of research designs: A meta-analysis study. *Computers and Education*, *125*, 345–357. http://dx.doi.org/10.1016/j.compedu2018.06.020.

Van der Graaf, J., Segers, E., & Verhoeven, L. (2016). Discovering the laws of physics with a serious game in kindergarten. *Computers and Education*, *101*, 168–178. http://dx.doi.org/10.1016/j.compedu.2016.06.006.

Van Eck, R. (2006). Digital game-based learning: It's not just the digital natives who are restless.... *Educause Review*, *41*(2), 16–30.

Verbruggen, S., Depaepe, F., & Torbeyns, J. (2021). Effectiveness of educational technology in early mathematics education: A systematic literature review. *International Journal of Child-Computer Interaction*, *27*, Article 100220. http://dx.doi.org/10.1016/j.ijcci.2020.100220.

Vinter, A., Pacton, S., Witt, A., & Perruchet, P. (2010). Implicit learning, development and education. In J.-P. Didier, & E. Bigand (Eds.), *Rethinking Physical and Rehabilitation Medicine* (pp. 111–127). Springer Verlag, http://dx.doi.org/10.1007/978-2-8178-0034-9_6.

Vinter, A., & Perruchet, P. (1999). Isolating unconscious influences: The neutral parameter procedure. *The Quarterly Journal of Experimental Psychology Section A, 52A(4)*, *85*, 7–875. http://dx.doi.org/10.1080/027249899390846.

Vygotsky, L. S. (1978). *Mind in society*. Harvard University Press.

Walker, H. (2010). Evaluating the effectiveness of apps for mobile devices. *Journal of Special Education Technology*, *30*(1), 59–63.

Wang, L. C., & Chen, M. P. (2010). The effects of game strategy and preference-matching on flow experience and programming performance in game-based learning. *Innovations in Education and Teaching International*, *47*(1), 39–52. http://dx.doi.org/10.1080/14703290903525838.

Wang, Y. L., Hou, H. T., & Tsai, C. C. (2020). A systematic literature review of the impacts of digital games designed for older adults. *Educational Gerontology*, *46*, 1–17. http://dx.doi.org/10.1080/03601277.2019.1694448.

Wastiau, P., Kearney, C., & Van den Berghe, W. (2009). *How are digital games used in school?*. European Schoolnet, Retrieved from http://games.eun.org/upload/gis-full_report_en.pdf.

Wouters, P., van Nimwegen, C., van Oostendorp, H., & van der Spek, E. D. (2013). A meta-analysis of the cognitive and motivational effects of serious games. *Journal of Educational Psychology*, *105*, 249–265. http://dx.doi.org/10.1037/a0031311.

Wu, Q., Zhang, J. W., & Wang, C. Y. (2020). The effects of english vocabulary learning with digital games and its influencing factors based on the meta-analysis of 2160 test samples. *International Journal of Emerging Technologies in Learning*, *15*(17), 85–100. http://dx.doi.org/10.3991/ijet.v15i17.11758.

Xu, Z. H., Chen, Z., Eustler, L., & Geng, Z. (2020). A scoping review of digital game-based technology on English language learning. *Educational Technology Research and Development*, *68*(3), 877–904. http://dx.doi.org/10.1007/s11423-019-09702-2.

Zhang, L., & Treiman, R. (2021). Preschool children's knowledge of letter patterns in print. *Scientific Studies of Reading*, *25*(5), 371–382. http://dx.doi.org/10.1080/10888438.2020.1801690.