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Enhanced disengagement of auditory attention and phonological skills in action video gamers

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ABSTRACT

Video games play a major role in the everyday life of children, teenagers, and adults. Several studies show that action video games (AVGs) improve visual attentional efficiency. AVGs also appear to improve reading speed and phonological skills in children with developmental dyslexia. These results have been linked to the intrinsic characteristics of AVGs, in which fast disengagement of multisensory attention allows for efficient extraction of relevant dynamic information, a skill that is crucially also involved in phonological and reading skills. We tested the hypothesis that AVG players demonstrate faster auditory attention disengagement in an auditory spatial cuing task, as well as better phonological and reading performance than non-players. We found that AVG players were faster in spatial localization of auditory targets and showed enhanced attentional disengagement as indexed by a smaller cuing effect. AVG players also showed better phonological decoding and working memory skills. Moreover, the beneficial effects of AVGs, as measured by faster attentional disengagement, were linked to better phonological and reading skills in adult AVG players. We suggest that a more efficient attentional disengagement - controlled by the posterior parietal cortex - induces enhanced multisensory processing in AVG players.

1. Introduction

Over the past few decades, video games have started to play a major role in the everyday life of children, teenagers, and adults (Sauce, Liebherr, Judd, & Klingberg, 2022). Research on a particular genre of video games, so-called action video games (AVGs), has demonstrated that regular players have improved perceptual and attentional abilities (for reviews see Bavelier & Green, 2019; Green & Bavelier, 2012). Recent studies highlight that playing AVGs may also be related to a benefit in reading abilities (Antzaka et al., 2017) and could serve as complementary training to improve reading fluency in children with developmental dyslexia (DD) (Franceschini & Bertoni, 2019; for reviews see; Franceschini et al., 2015; Peters, De Losa, Bavin, & Crewther, 2019).

AVGs are characterized by high-speed events and fast-moving targets, high perceptual, cognitive and motor loads, emphasis on the peripheral visual field and spatial and temporal unpredictability (Bavelier & Green, 2019; Green & Bavelier, 2012). Examples of these games are first- and third-person shooter (FPS, TPS, i.e., Call of Duty, Fortnite, etc.) or action role-playing games (RPG, i.e., Dark Souls, Assassin's Creed, etc). Based on the unique characteristics of the AVGs, different cognitive processes might be taxed, but for them to be a successful learning platform they should all have characteristics known to develop time-on-task and promote more effective learning (Green & Bavelier, 2015). However, like most fields, there is still an active debate. Not all studies find significant correlations between AVG experience and cognitive abilities (Unsworth et al., 2015), but this often depends on methodological differences between studies (Green et al., 2017). Unsurprisingly, many correlational and training studies have shown that playing AVGs can be associated with higher visual attentional skills, including processes tapping into visual target detection and discrimination (Castel, Pratt, & Drummond, 2005), the size of the visual field (Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003), contrast discrimination (Li, Polat, Makous, & Bavelier, 2009), mental rotation (Feng et al., 2007), the attentional blink (Green & Bavelier, 2003), and the visual attention span (Antzaka et al., 2017). Importantly, efficient visual attention mechanisms support fluent reading (Bosse & Valdois,

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2009; Ekstrand, Neudorf, Kress, & Borowsky, 2020; Ekstrand, Neudorf, Kress, & Borowsky, 2019; Facoetti, 2012; Peters et al., 2019; Vidyasagar & Pammer, 2010), and accordingly, playing AVGs has been shown to directly relate to better reading skills and performance on reading-related visual attentional tasks (Antzaka et al., 2017; Bavelier, Green, & Seidenberg, 2013; Franceschini et al., 2013; Peters, Crewther, Murphy, & Bavin, 2021).

In addition to visual attentional processes, beneficial effects of playing AVGs on reading skills have been reported on tasks that tax phonological skills such as phonological decoding (Bertoni, Franceschini, Ronconi, Gori, & Facoetti, 2019; Franceschini & Bertoni, 2019; Franceschini et al., 2013) and phonological short-term and working memory in training studies (Franceschini & Bertoni, 2019; Franceschini et al., 2017). For example, Franceschini et al. (2013) demonstrated that after 12 h of AVG training, pseudo-word phonological decoding and word text reading were both significantly improved in Italian children with DD. These results were replicated in other studies by Franceschini et al. (2017), who also showed an improvement in phonological short-term memory in English children with DD and Bertoni et al. (2019) who showed enhancement in reading and faster phonological decoding. These are potentially very important findings given that phonological deficits are frequently associated with reading disabilities (Saksida et al., 2016), and training such skills has been demonstrated to improve reading (Alexander, Andersen, Heilman, Voeller, & Torgesen, 1991; Kjeldsen, Educ, Saarento-Zaprudin, & Niemi, 2019; Temple et al., 2003; Torgesen, 2005). If AVG training indeed leads to improvements in both reading (Gambacorta et al., 2018; Vedamurthy et al., 2015) and phonological skills, this could provide an interesting alternative or addition to traditional phonological training programs (Bertoni et al., 2019; Franceschini & Bertoni, 2019; but see; Łuniewska et al., 2018).

However, explaining the link between playing AVGs and improved phonological skills is not as intuitive as assuming that AVGs and reading are linked through a common visual attentional component. The multisensory nature of the plasticity of the fronto-parietal attentional network (Facoetti, 2012; Vidyasagar & Pammer, 2010) could explain both the reading and phonological improvements induced by AVG training in children with DD (Franceschini & Bertoni, 2019) not only through a boost of visual attention but also of auditory attention. Given that poor auditory attentional processing has been linked to poor phonological processing (Facoetti, 2012; Facoetti et al., 2010; Lallier, Donnadieu, & Valdois, 2013), it is reasonable to assume that AVGs could boost phonological skills by enhancing attentional processing skills in the auditory (in addition to the visual) modality. Alternatively, an auditory boost induced by AVG experience could be explained by the fact that, besides the central visual characteristics of AVGs, these games also substantially stimulate auditory processing skills, through, for example, sounds indicating position in space, sounds that set the mood of the game, thumping background music, sounds that indicate that danger has passed, or all enemies have been eliminated and so on (Stewart, Martinez, Perdew, Green, & Moore, 2020).

Studies on reading acquisition and DD have previously highlighted the important role of auditory attentional processing in the adequate development of phonological processing skills, and they align with theories that link rapid temporal processing in both the auditory and visual modalities to reading development (Boets et al., 2011; Goswami, Power, Lallier, & Facoetti, 2014; Tallal, 1980, 2004). One of these hypotheses is the "Sluggish Attentional Shifting" (SAS) theory, which postulates that when individuals with DD have to process rapid stimuli sequences, their automatic attention does not disengage fast enough from an item in order to process the following one (Hari & Renvall, 2001; Lallier et al., 2009). Interestingly, Hari and Renvall (2001) postulate that the source of this attentional deficit lies in the parietal lobe, a structure that has previously been associated with multisensory attentional processing (Andersen, Snyder, Bradley, & Xing, 1997; Bremmer et al., 2001). Accordingly, they propose that the causal link between reading deficits and phonological problems involves sluggish automatic attentional shifting *across all sensory modalities*. In particular, they suggest that auditory attention disengagement may play a fundamental role in reading through both phoneme discrimination - necessary for phonological decoding through graphene-to-phoneme mapping - and phonological short-term memory (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014). Supporting this hypothesis, studies have shown a significant link between auditory attentional shifting skills and both phonological processing and reading, using several tasks involving the rapid serial presentation of auditory stimuli, such as attentional blink tasks (Lallier, Donnadieu, Berger, & Valdois, 2010), auditory stream segregation tasks (Lallier et al., 2009; Lallier, Tainturier, et al., 2010), auditory spatial attentional orienting tasks (Facoetti, Lorusso, et al., 2003; Facoetti et al., 2005, 2010), and audio-visual oddball tasks (Meyer & Schaadt, 2020). If reading-related attentional benefits for AVG players are observed in the auditory modality (Green, Pouget, & Bavelier, 2010), this would suggest that the previously reported association between playing AVGs and the enhancement of reading skills is probably not solely mediated by a boost of visual attention skills. More specifically, AVG-related improvements in auditory attentional shifting could explain why children with DD who receive AVG training improve not only their reading abilities (which involve a visual processing component) but also their "auditory" phonological skills.

In the present study, we investigated whether AVG players demonstrate faster automatic (i.e., exogenous in the present case) disengagement of auditory attention and whether this enhancement could be associated with advantages in phonological and reading skills. We tested the reading and phonological skills of two groups of participants, namely AVG players and non-players (NAVG). Attentional shifting in the auditory modality was measured with a spatial attentional orienting paradigm (Facoetti et al., 2010, 2005; Facoetti, Lorusso, et al., 2003; Mayer, Franco, & Harrington, 2009; Mondor & Bryden, 1992; Posner, 1980) which has been proven to be sensitive to capture the relation between multisensory attentional processing and reading performance ((Facoetti et al., 2010, 2005; Facoetti, Lorusso, et al., 2003). In the task used in the present study, an uninformative auditory cue was presented to the left or right ear, followed by an auditory target that was presented to the same (valid condition) or the other (invalid condition) ear. In addition, we manipulated the time between the onsets of the cue and the target (stimulus onset asynchrony - SOA) to explore group differences on the time-course of attentional shifting skills. This paradigm allowed us to determine whether AVG players show faster attentional disengagement compared to NAVG players, as indexed by (i) the size of their cuing effects (i.e., RT differences between invalid and valid conditions) and (ii) the time course of their inhibition of return (IOR). Large cueing effects have been shown to indicate less efficient, hence slower, attentional disengagement (Losier & Klein, 2001). In addition, when IOR occurs, at longer SOAs, RTs are faster for the invalid condition. This is caused by the orienting of attention towards a location and the subsequent removal of attention from that location, to discourage attention from re-orienting back to the originally attended one. This could serve to facilitate target search and could indeed reflect faster skills (Klein, 2000). Therefore, if AVG playing experience enhances the auditory attentional shifting skills subtending phonological and reading development, we would expect AVG players to exhibit smaller cuing effects and earlier IOR than NAVG players. Indeed, a beneficial effect of AVGs was already found in auditory attentional processing as well as visual attentional processing in studies comparing AVG and NAVG players (Feng & Spence, 2018; Föcker, Cole, Beer, & Bavelier, 2018; Franceschini et al., 2013, 2017; Green & Bavelier, 2003; Wu et al., 2021) and in training studies (Franceschini et al., 2013, 2017; Green & Bavelier, 2003), as in the study of Franceschini et al. (2013) in which children showed improvement in cross-modal alerting in a spatial attentional task. However, no study to date has shown a difference in the speed of attentional disengagement between AVG and NAVG players.

As for reading and phonological skills, we expected the AVG group to show better reading performance only on challenging reading tasks (see *2.1.4.3* and *2.1.4.4*) as participants in both groups were skilled readers and were expected to perform equally well on classical reading tasks (Antzaka et al., 2017; Franceschini et al., 2013, 2017). In addition, we expected the AVG group to perform better on phonological short-term and working memory tasks (Franceschini & Bertoni, 2019; Franceschini et al., 2017) and on the phonemic awareness task, given that these tasks were designed to be challenging.

2. Present study

2.1. Materials and methods

2.1.1. Participants

A total of 48 native Spanish speakers (who also knew either Basque or English as second language), right-handed adults (4 females and 44 males), mean age 26.21 years (18–44 years old), with non-verbal IQ within the typical range (mean = 114.51, range = 90–130), no hearing impairments or reading difficulties, participated in the experiment. Participants were divided into two groups: AVG players and NAVG players. AVG players were mainly recruited through advertising on social media while NAVG players were mainly recruited through the participant website of the Basque Center on Cognition Brain and Language (BCBL). Information about the participants' age, level of education at the time of the study, bilingualism history, and video games playing experience can be found in the supplementary materials (S2).

To be included in the AVG group, participants had to have played AVGs (mostly FPS, TPS or RPG, but there was a lot of variability in the games played by the participants, see S2) regularly, meaning at least 4 h a week, during the six months prior to the study. This cut off was chosen based on the existent literature in the field (see Bediou. et al., 2018 for a meta-analysis). Information on each participant's level of experience at playing AVGs was acquired from a questionnaire that also included questions about experience in other leisure activities (e.g., "Have you played video games in the past six months? How often?"; "Have you played a musical instrument in the past six months? How often?"; "Have you practised sports in the past six months? How often?", see supplementary materials S1), in order to minimise any expectations on the study, and the participant's performance, that could have been created by the advertisement (Green et al., 2019). Descriptive data extracted from this questionnaire is presented in Table 1. Twenty-five participants (2 females) complied with the recruitment criteria for the AVG group (mean age = 24.32, *SD* = 6.16, range = 18–41), while 23 participants (2 females) fell into the NAVG group (mean age = 28.26, *SD* = 8.51, range = 19–44).

The BCBL review board approved the experiment in accordance with the principles of the Declaration of Helsinki, and each participant signed an informed consent form prior to the experiment and was paid for participating.

Table 1
Descriptive statistics regarding participants' leisure activities.

	AVG (n = 25) M *(SD)* range		NAVG (n = 23) M *(SD)* range		Independent test comparisons
Non-verbal IQ	114.52 *(9.53)*	90–130	114.0 *(8.37)*	93–126	*U* = 206.00 r = −.283
Hours of AVG played/ week	**7.24 *(4.28)***	**4–21**	**0.08 *(0.29)***	**0–1.0**	***U* = 575.0****r* = 1.000**
Hours of Music played/ week	1.20 *(3.37)*	0–12	1.00 *(3.11)*	0–14	*U* = 264.0 *r* = −0.082
Hours of Sports/ week	3.58 *(3.16)*	0–10	3.57 *(3.17)*	0–12	*U* = 291.0 *r* = 0.023

*p < .05, **p < .01, ***p < .001.
Mean (SD) and maximum and minimum (i.e., range) of hours spent playing action video games and practising music or sports. The right column reports the independent test comparison and the group effect size.

2.1.2. Tasks

Participants performed different tasks that allowed us to measure skills of interest such as reading, phonological processing and auditory attention as well as control skills (i.e., non-verbal IQ).

The experimental procedure and data acquisition were controlled with OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) running on a 19" ViewSonic CRT G90fB, except for the reading and IQ tasks.

2.1.2.1. IQ - the Kaufman brief intelligence test (K-BIT) - matrices subtest (Kaufman & Kaufman, 2004). The K-BIT matrices subtest measures non-verbal reasoning skills via 48 items. It required the participant to analyse a target picture or a target series of pictures. The participant was instructed to choose the picture that matched and related to the target amongst multiple options. Stimuli could represent people, objects, or geometric shapes and symbols. In the first 29 trials (the easier ones) the participants were asked to select, from five options, the one that best matched the target picture (for example choosing a bone in relation to a dog, or a car in relation to a truck). Further on, the target was a four-figure pattern, and the participant had to select among six or eight options which figure best completed this pattern (for example if a hat was placed on the head, a shoe was placed on a foot). Total accuracy was recorded with standard scores.

2.1.2.2. Auditory spatial attentional orienting task. The participant sat at a distance of 50 cm from the screen, with headphones on. Participants were instructed to fixate a central cross throughout the experiment and not to close their eyes. After the first 500 ms of each trial, a 40 ms auditory cue (white noise) was presented to the right or left ear followed by a 20 ms auditory target (pure tone, 2500 Hz). The cue was followed by variable intervals of 0, 30, 80, 280 or 780 ms, leading to SOAs of 40, 70, 120, 320 and 820 ms. SOAs were randomised across trials. The target was either presented to the same ear as the cue (valid condition) or to the opposite ear (invalid condition). Participants were asked to localise the target ear as quickly and as accurately as possible by pressing the letter "M" if they heard the target sound to the right ear and the letter "Z" if they heard the target sound to the left ear. The maximum time for response was set to 1500 ms. As soon as the participant responded or the maximum time allowed for a response expired, the next trial began. The probability that the target would appear in the same or a different location from the cue was 50%, such that the cue was non-predictive of target location (there were an equal number of valid and invalid trials). There was a total of 240 trials, 12 trials for each experimental condition (right and left target, valid and invalid conditions and five SOAs). Participants were initially presented with 20 practice trials for which feedback was provided. A break was provided halfway through the task. The total duration of the experiment was approximately 7 min.

2.1.3. Phonological tasks

Three phonological tasks tapping into different processing were administered to the participants. One measured phonological short-term memory, one measured phonological working memory and the last measured phonemic awareness.

2.1.3.1. Forward syllable repetition (FSR). The forward syllable repetition task was used to measure phonological short-term memory. Each trial consisted in participants listening to a sequence of CVC syllables through headphones. After listening to each sequence, they were asked to repeat the sequence, respecting the order of the syllables. Following the participant's response, the experimenter pressed a key to proceed to the next trial. Participants' responses were recorded. Stimuli consisted of 14 lists ranging from two to eight syllables (two items of each length).

All syllables had a CVC structure (e.g.,/bif/). The CVC syllable stimuli were recorded by a native Spanish speaker and presented in a fixed order from shorter to longer lists. If both items from a list were wrongly reported, the experimenter would stop the experiment. Participants' accuracy was calculated based on the total number of correctly repeated phonemes across the 14 lists (total number of phonemes = 210).

2.1.3.2. Backward syllable repetition (BSR). The backward syllable repetition task was used to measure phonological working memory. The stimuli and procedure were the same as in the FSR task, but participants were asked to repeat the list of syllables in reverse order (from the last syllable heard to the first one). Participants' accuracy was calculated based on the total number of correctly repeated phonemes across the 14 lists (total number of phonemes = 210).

2.1.3.3. Phoneme deletion. This task was used to measure phonemic awareness. In each trial participants were presented with a pseudoword over headphones (e.g.,/neɣuti/) followed by a single phoneme (e.g.,/n/). Participants were instructed to repeat the pseudoword without the phoneme (e.g.,/eɣuti/). After a response was given, the experimenter pressed a key to proceed to the next trial. Stimuli consisted of 24 6-to-8 letter-long pseudowords. The position of the to-be-deleted phoneme was manipulated so as to include an equal number of stimuli with the to-be-deleted phoneme in the first, second, and third syllables of the pseudowords. The pseudowords and the phonemes were recorded by a Spanish native speaker. Stimuli were presented in fixed order. The responses were recorded, and the total accuracy (/24) was calculated for each participant.

2.1.4. Reading tasks

Four reading tasks tapping into different reading processes were administered to the participants. Two tasks were aimed to measure the general reading proficiency of participants (fluency and comprehension). Two other tasks, considered more challenging, tapped into reading processes for which participants could not rely as much on their semantic (meaningless text) or lexical (pseudoword text) knowledge, inducing more controlled reading strategies.

2.1.4.1. Text reading. Participants had to read aloud a newspaper text as quickly and as accurately as possible until they reached the end of the text. They were recorded while reading the text and their total reading time was measured. Individual scores included reading speed and reading errors. Reading speed was calculated as the number of read syllables per second (syll/sec). Reading errors were calculated by assigning one error for each word that was not pronounced correctly, without including self-corrections.

2.1.4.2. Text reading with comprehension. Participants were presented with a newspaper text and asked to read it aloud as quickly and as accurately as possible until they reached the end of the text. They were informed, beforehand, that after reading the text they would have to respond to four written questions. Participants were recorded while reading the text and their total reading time was measured. Individual scores from this task included reading speed, reading errors, and comprehension. Reading speed was calculated as the number of read syllables per second (syll/sec). Reading errors were calculated by assigning one error for each word that was not pronounced correctly, without including self-corrections. Comprehension was measured by assigning one point for each correct answer to the four comprehension questions.

2.1.4.3. Meaningless text reading. Participants were presented with a Spanish adaptation of the French text "L'Alouette" (Lefavrais, 1967). The text includes a large proportion of very low frequency words and pseudowords, and although grammatically congruent, this text is associated with a low frequency semantic content. Participants were instructed to read the text aloud as quickly and as accurately as possible until they reached the end of the text. Participants were recorded and their total reading time was measured. Individual scores from this task included reading speed and reading errors. Reading speed was calculated as the number of read syllables per second (syll/sec). Reading errors were calculated by assigning one error for each word that was not pronounced correctly, without including self-corrections.

2.1.4.4. Pseudoword text reading. This task was used to measure reading skills taxing phonological decoding fluency. Participants were presented with a text that was exclusively composed of pseudowords. They were instructed to read the text aloud as quickly and as accurately as possible until they reached the end of the text. Participants were recorded and their total reading time was measured. The 5-row long text included pseudowords composed of 1–3 syllables (CV, CCV, CVCV, CCVCV, CVCVCV, CCVCVCV) for a total of 100 syllables. Individual scores included reading speed and reading errors. Reading speed was calculated as the number of read syllables per second (syll/sec). Reading errors were calculated by assigning one error for each word that was not pronounced correctly, without including self-corrections.

2.1.5. General procedure

The whole experimental session was conducted individually in a quiet dimly lit (spatial attentional orienting task) and normally lit (reading and phonological tasks) room during a 30-min session. Beyerdynamic DT 770 Pro 250OHM headphones were used. All tasks were administered in Spanish. The order of tasks was counterbalanced across participants, although the text reading task was always presented after the text reading with comprehension and the BSR was always presented after the FSR.

After the session, participants completed a questionnaire regarding their gaming, music, and sports habits.

2.1.6. Data analyses

The auditory spatial attentional orienting task was analysed using a type III ANOVA (JASP Team, 2020) including group (AVG and NAVG) as the between-subject factor, and SOA (40, 70, 120, 320 and 820 ms), and cue condition (valid and invalid) as within-subject factors. One participant in the NAVG group was removed from the analysis because their accuracy was below 70%. Moreover, RTs faster than 150 ms were excluded and RTs above or below 2.5 standard deviations (SD) from the mean by participant and condition were excluded. This resulted in the removal of approximately 4% of all observations. The two groups were compared on the control variables (chronological age and non-verbal IQ) using two-tailed parametric t-tests. Group effects on text reading and text reading with comprehension were assessed with two-tailed parametric t-tests. Group effects on the phonological tasks and the most challenging reading tasks (i.e., pseudoword and meaningless text reading) were assessed using one-tailed t-tests because group differences were *a priori* expected on these tasks (Franceschini & Bertoni, 2019; Franceschini et al., 2017). One-tailed Pearson correlations were conducted to confirm our *a priori* hypotheses that spatial attentional orienting, reading and phonological processing skills should be positively related. In order to reduce the number of correlations run, we used composite measures between tasks that strongly correlated across the whole group and reflected similar theoretically relevant constructs.

In case of non-normal data distribution or unequal variance between groups, Mann-Whitney U tests and Welch's *t*-test were used, respectively. In case of violation of the multivariate and bivariate assumptions of normality, Kendall correlations were used. Bonferroni corrections were applied to post-hoc comparisons and correlations.

3. Results

3.1. Participants characteristics

The two groups of participants did not differ significantly either on age ($U = 206.00$, $p = .09$, $r = -0.283$) or non-verbal IQ measurements ($U = 281.00$, $p = .72$, $r = 0.062$.) (IQ measures were not available for two participants). In addition, no group difference was found on the hours spent at other leisure activities such as musical ($U = 264.00$, $p = .47$, $r = -0.082$) or sport ($U = 291.00$, $p = .95$, $r = 0.012$) practices, but a significant difference was found for the hours spent playing AVGs ($U = 575.00$, $p < .001$, $r = 1.000$).

3.2. Auditory spatial attentional orienting

Overall target localization accuracy was very high across all participants ($M = 93.46\%$, $SD = 5.37$) and the two groups did not differ significantly (AVG: $M = 94.27\%$, SD = 4.91; NAVG: $M = 92.54\%$, SD = 5.84, $U = 322$, $p = .321$, $r = 0.171$). In addition, accuracy did not differ between groups on valid and invalid conditions, when looked at separately (AVG valid accuracy: M = 98,53%, SD = 0.05; invalid accuracy: M = 91,58%; SD = 0,07; NAVG valid accuracy: M = 97,98%, SD = 0.04; invalid accuracy: M = 87,99%, SD = 0.09; $U = 306.50$, $p = .402$, $r = 0.115$; $U = 344.50$, $p = .141$, $r = 0.253$). Furthermore, there was no speed and accuracy trade-off in the AVG group, as reflected by the negative correlation between speed and accuracy, indicating that the AVG players responding faster were not the ones making more errors, but the opposite ($r = -.464$, $p = .020$).

Regarding RT measures, significant main effects of SOA ($F(4,180) = 122.23$, $p < .01$, $\eta^2 = 0.236$) and cue condition ($F(1,45) = 83.39$, $p < .001$, $\eta^2 = 0.071$) were found as well as a significant SOA by cue condition interaction ($F(4,180) = 56.24$, $p < .01$, $\eta^2 = 0.072$, Fig. 1). Follow-up post-hoc comparisons indicated that there was a significant cuing effect, with faster RTs in the valid cue condition than the invalid cue condition, at the first three SOAs (40, 70, 120 ms, $ps < .001$, $d = 1.370$, $d = 1.306$, $d = 0.811$ respectively) but no cuing effect was found at 320 ms ($p > .10$, $d = 0.136$). In addition, the cuing effect was reversed, with faster RTs in the invalid cue condition than the valid cue condition, at the longest SOA (820 ms, $p < .001$, $d = -0.562$), indicating the IOR effect.

In addition, there was a significant group main effect on RTs ($F(1, 45) = 5.92$, $p = .01$, $\eta^2 = 0.051$), showing that AVG players were overall faster at localising the auditory targets. However this group effect was modulated by the cue condition as illustrated by the significant group by cue condition interaction ($F(1,45) = 5.54$, $p = .023$, $\eta^2 = 0.005$, Fig. 2). The post-hoc comparisons indicated that the AVG group responded significantly faster than the NAVG group in the invalid cue condition only ($p = .02$, $d = -0.811$; valid: $p = .084$, $d = -0.619$). Moreover, although both groups showed a significant cuing effect ($ps < .001$), it was smaller in the AVG group (M = 46 ms, SD = 42) compared to the NAVG group (M = 73 ms, SD = 50; $t = -2.03$, $p = .049$, $d = -0.593$).

Finally, the group by cue condition by SOA interaction on RTs was not significant ($F(4,180) = 0.93$, $p = .45$, $\eta^2 = 0.001$).

3.3. Phonological and reading skills

The descriptive statistics regarding the performance obtained on the phonological and reading tasks are presented in Table 2 for the two groups. In the phonological tasks, participants in the AVG group performed better than the NAVG group in the BSR task, but not in the FSR task, showing that the AVG group repeated a significantly higher number of phonemes only when phonological working memory was measured (BSR: $U = 373.5$; $p = .039$; FSR: $U = 299.5$; $p = .406$). No difference was found on phonemic awareness (phoneme deletion task: $U = 294.0$, $p = .45$). As expected, no group difference was found on the "easiest" text reading tasks neither for accuracy, nor for reading speed (text reading and text reading with comprehension accuracy and reading speed: all $ps > .09$). Regarding the more challenging of reading tasks, the two groups differed significantly in the number of errors in the pseudoword text ($W = 179.5$, $p = .011$), with the NAVG group making more errors than the AVG group. In addition, a marginal difference was found in the number of errors in the meaningless text ($W = 217$, $p =$

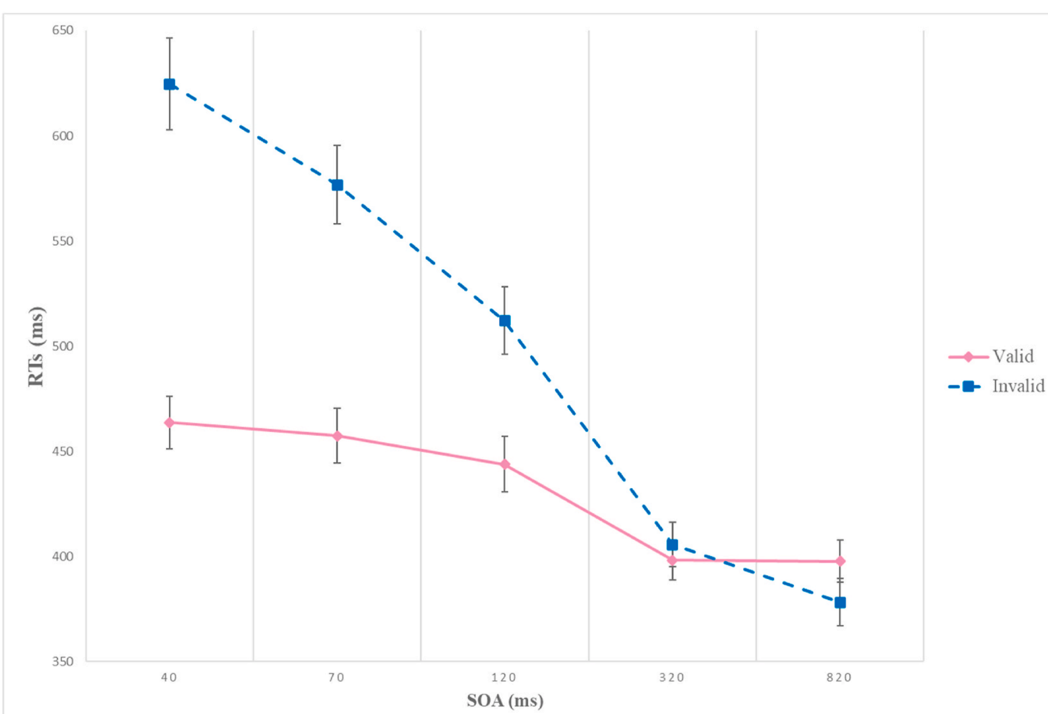

Fig. 1. SOA by cue condition interaction.
SOA by cue condition interaction on the auditory spatial attentional orienting task (errors bars represent the standard error).

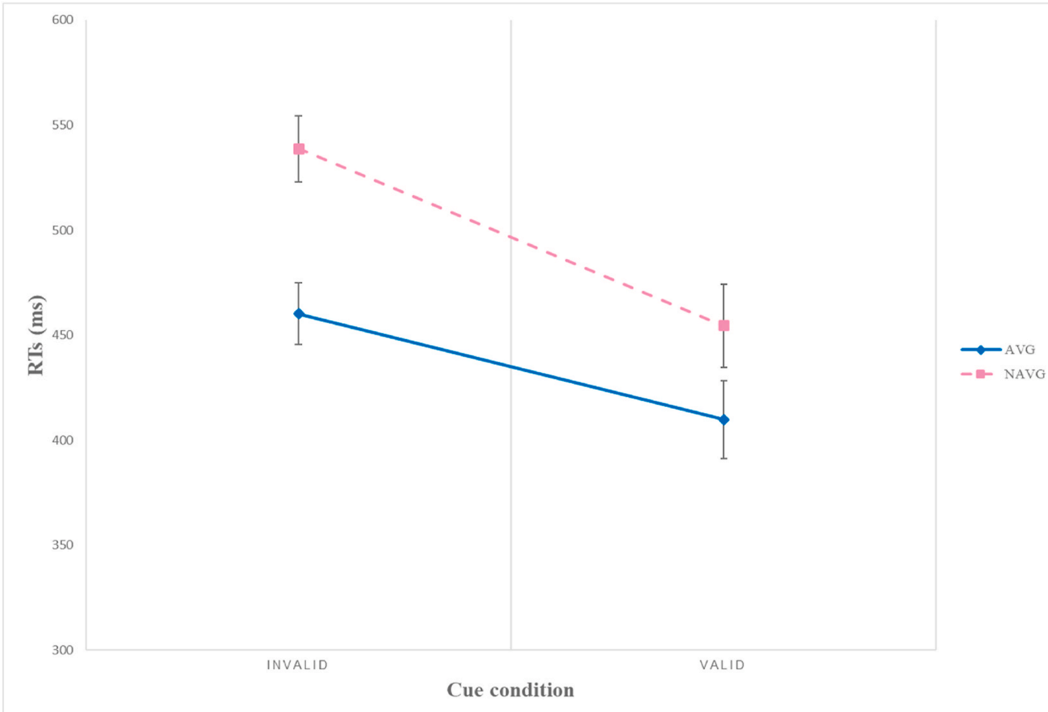

Fig. 2. Group by cue condition interaction.
Group by cue condition interaction on the auditory spatial attentional orienting task (errors bars represent the standard error).

Table 2
Descriptive statistics for AVG and NAVG.

	AVG (n = 25) M *(SD)* range		NAVG (n = 23) M *(SD)* range		Independent test comparisons
Forward syllable repetition accuracy (/210)	67.40 *(23.84)*	25–107	60.09 *(23.90)*	10–81	$W = 299.5$; $r = 0.042$
Backward syllable repetition accuracy (/210)	**49.84 *(25.47)***	**21–110**	**35.65 *(22.63)***	**9–80**	**$W = 373.5^*$; $r = 0.299$**
Phoneme Deletion Accuracy (/24)	18.08 *(4.16)*	8–23	17.74 *(5.32)*	2–24	$W = 294.0$; $r = 0.023$
Text Reading with Comprehension	5.79 *(0.76)*	4.11–6.94	5.86 *(1.14)*	2.83–8.70	$t = -0.235$; $d = -0.068$
Speed (syll/sec.)	15.76 *(11.84)* 2.28 *(1.06)*	2–50	14.96 *(11.12)* 2.44 *(1.08)*	3–52	$W = 298.5$; $r = 0.038$
Errors		0–4		1–4	$W = 266.0$; $r = -0.075$
Correct answers to questions (/4)					
Text Reading	6.03 *(0.74)*	4.52–7.22	6.05 *(1.26)*	3.13–9.38	$t = -0.080$; $d = -0.023$
Speed (syll/sec.)	3.36 *(3.09)*	0–13	4.83 *(4.08)*	0–15	$W = 229.0$; $r = -0.203$
Errors					
Pseudoword Text Reading	2.80 *(0.48)*	1.60–3.18	2.99 *(0.75)*	1.52–4.70	$t = -1.012$; $d = -0.295$
Speed (syll/sec.)	**1.12 *(1.20)***	**0–5**	**2.26 *(1.96)***	**0–8**	**$W = 179.5^*$; $r = -0.376$**
Errors					
Meaningless Text Reading	4.66 *(0.68)*	3.37–5.83	4.95 *(1.16)*	2.49–7.93	$t = -1.057$; $d = -0.308$
Speed (syll/sec)	4.16 *(3.67)*	0–16	5.17 *(3.27)*	0–14	$W = 217.0$; $r = -0.245$
Errors					

*p < .05, **p < .01, ***p < .001.
Mean (SD) and Range of performance on phonological and reading tasks. The right column reports the independent test comparison (*t*-test or Wilcoxon-Mann-Whitney U or Welch's *t*-test based on the assumption of variance and normality) and effect size (with r values for the Wilcoxon-Mann-Whitney test and d values for the t-tests or Welch's t-tests) of the two groups.

.073), with the NAVG group making more errors than the AVG group.

3.4. Correlations analyses

Given that a significant group by cue condition (but no group by cue condition by SOA) interaction was found, we computed the mean of cuing effects across all SOAs for each participant, as an index of the efficiency of auditory attentional disengagement (note that smaller cuing effects are thought to reflect more efficient attentional disengagement; Losier & Klein, 2001). Moreover two composite scores reflecting theoretically relevant constructs were computed: a phonological composite score, computed by averaging performance obtained on the three auditory phonological tasks, i.e., FRS, BRS and phoneme deletion (for all correlation coefficients, ps < .02) and a text reading composite score, tapping into lexical reading processes, and obtained by averaging the text reading, text reading with comprehension and meaningless text reading tasks (for all correlation coefficients, ps < .001). We maintained the pseudoword reading task by itself as it is supposed to reflect the construct of phonological decoding that none of the other tasks measured. The cuing effect significantly correlated with the phonological composite score (Fig. 3) both within the AVG group (r(n = 25) = −0.550, p = .002) and across all participants (r(n = 47) = −0.343, p = .009), indicating that smaller cuing effects were linked to better phonological skills. This correlation was not found within the

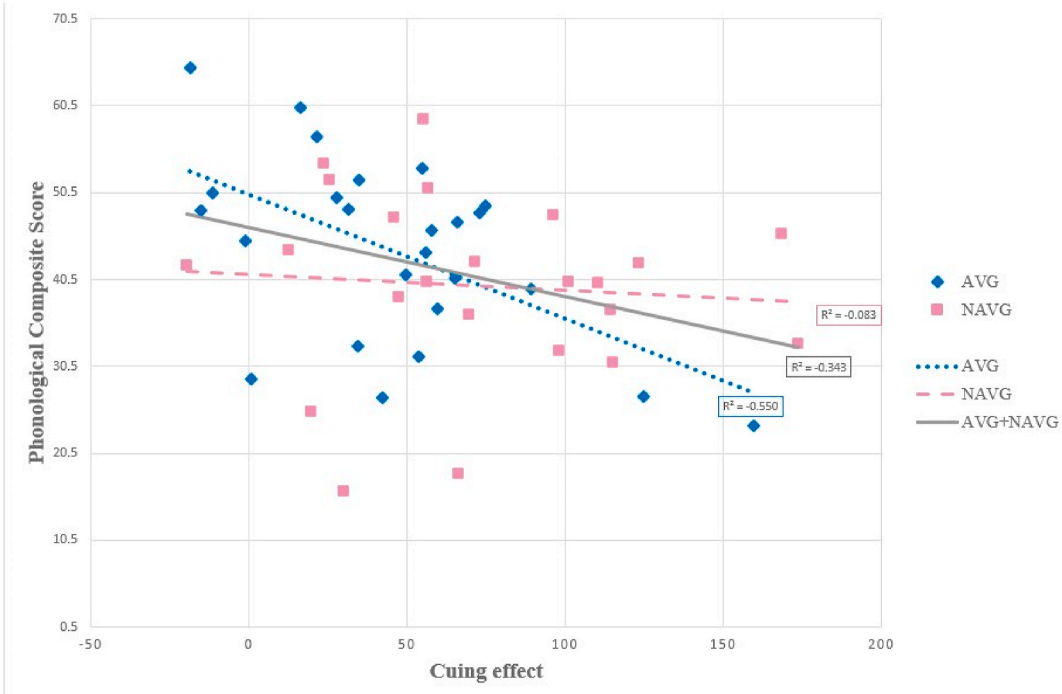

Fig. 3. Correlations between cuing effects (invalid RTs – valid RTs) and the Phonological Composite Score.

NAVG group (r(n = 22) = −0.083, p > .10).

Moreover, the cuing effects significantly correlated with the reading composite score (Fig. 4) within the AVG group (r(n = 25) = −0.435, p = .015) but neither across all participants, (note the trend in the right direction (r(n = 47) = −0.151, p = .155), nor in the NAVG group (r(n = 22) = −0.047, p > .10) indicating that AVG players with smaller cuing effects were faster readers. No correlation between the cuing effect and the pseudoword text reading was found neither across all participants (r (n = 47) = −0.061, p = .341), nor within the AVG group (r(n = 25) = −0.257, p = .107 or NAVG group (r(n = 22) = −0.006, p > .490).

Overall, these results suggest that smaller cuing effects indexing faster/more efficient disengagement of auditory attention were related to better performance on phonological and reading tasks, for the AVG players in particular.

4. Discussion

The aim of the present study was to test the hypothesis that

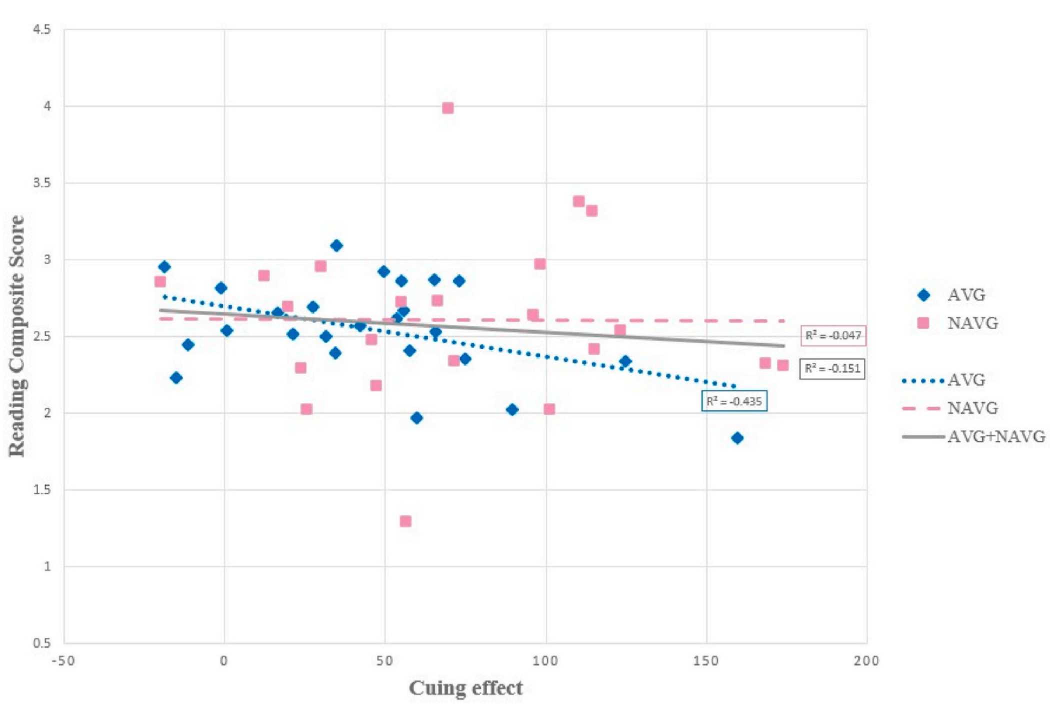

Fig. 4. Correlations between cuing effects and the Reading Composite Score.

enhancement of auditory attentional disengagement could underlie the relations between AVG playing experience, phonological, and reading skills. To this end, we assessed the performance of two groups of typical adult readers with or without AVG playing experience (AVG and NAVG) on an auditory spatial attentional orienting task, and a series of phonological and reading tasks. We expected AVG players to demonstrate faster attentional disengagement than NAVG players. As expected, AVG players showed overall faster spatial localization of auditory targets and faster attentional disengagement as indexed by smaller cuing effects than non-players despite no group difference being observed on the IOR. Moreover, we expected faster attentional disengagement to relate to better performance on the phonological tasks (especially for the phonological short-term and working memory tasks) and the most challenging reading tasks (i.e., pseudoword text reading and meaningless text reading). Accordingly, we showed advantages for the AVG group (who exhibited faster attentional disengagement) on phonological decoding and phonological working memory, reflected by higher accuracy scores than the NAVG group in the pseudoword text reading task and in repeating sequences of syllables backward, respectively. Finally, we found that smaller cuing effects were linked to better phonological skills across participants (and within the AVG group) and to better reading skills, within the AVG group only. The results are further discussed in the following paragraphs.

In the auditory spatial attentional orienting task, our participants were, as expected, significantly faster when responding to valid compared to invalid trials at shorter SOAs (40, 70, 120 ms; see Klein, 2000). No cuing effect was found for the 320 ms SOA and the cuing effect was reversed (RTs for invalid trials were faster than RTs for valid trials) at the longest SOA (820 ms), indicating the IOR phenomenon (Klein, 2000). These results illustrate how the time course of attentional orienting unfolds and are in line with previous results from similar tasks in the auditory domain (Mondor, Breau, & Milliken, 1998; Schmitt, Postma, & De Haan, 2000).

A key finding of our study is that the AVG group was significantly faster than the NAVG group at localising an auditory target (Castel et al., 2005; Dye, Green, & Bavelier, 2009), but only when the cue was presented to the opposite side of the target (invalid condition). First, this result is in line with research suggesting that AVG players have faster stimulus-response mappings that lead to the rapid execution of responses to both visual and auditory targets in the environment (Castel et al., 2005; Dye et al., 2009; Green & Bavelier, 2003; Meyer & Schaadt, 2020). Second, it suggests that the AVG players are better at disengaging their auditory attention from the invalid cue location and are more efficient at reallocating attentional resources to a previously uncued position regardless of SOAs. Therefore, AVG players seem to exhibit more efficient allocation of attentional resources and more efficient shifting abilities than NAVG players when they are measured in the auditory domain and in an exogenous attentional task (but see Hubert-Wallander, Green, Sugarman, & Bavelier, 2011).

The effect of AVG playing on the efficient allocation of attentional resources has been reported previously implying that AVG players might have the flexibility to adjust their attentional strategies depending on the task at hand (Cain, Prinzmetal, Shimamura, & Landau, 2014). Indeed, AVGs tend to promote both faster disengagement and wider distribution of attention (Antzaka et al., 2017; Castel et al., 2005; Green & Bavelier, 2003; Wu et al., 2021).

This hypothesis fits well with our result showing an advantage for the AVG players on the localization of targets presented to the opposite side of a previous cue (invalid condition), resulting in faster RTs in the uncued location compared to the NAVG group. This attentional advantage shown in AVG players could be related to a general better attentional disengagement in spatial and temporal domain, which have both be related to more efficient reading and phonological processing skills (Hari & Renvall, 2001; Helenius, Uutela, & Hari, 1999; Jednoróg, Gawron, Marchewka, Heim, & Grabowska, 2014; Lallier, Donnadieu, et al., 2010; Lallier et al., 2009; Lallier, Tainturier, et al., 2010; Lallier, Thierry, & Tainturier, 2013). Accordingly, the AVG players of the present study exhibited better performance on phonological and reading tasks.

Overall, the present data suggests that the development of increased attentional resources attributed to playing AVGs may, in fact, occur in the auditory as well as the visual domains (also see Franceschini et al., 2017, 2013; Green et al., 2010, but see; Stewart et al., 2020). The source of this auditory attention advantages in AVG players could stem from: (i) a more efficient disengagement mechanism, in line with the classical Posner theory of attention (Posner, 1980), and (ii) a larger pool of attentional resources that can be spatially allocated outside the focus of attention in line with the zoom-lens theory (Eriksen & St. James, 1986).

A possible neurobiological basis of the AVG players' advantage in attentional disengagement could be a more efficient functioning of the posterior parietal cortex (PPC). Indeed, larger cuing effects driven by RTs on invalid conditions has been found in patients with posterior parietal damage, specifically in the right hemisphere (Losier & Klein, 2001). Moreover, it has been demonstrated that efficiency of spatial disengagement was enhanced (faster RTs following invalid spatial cues) by transcranial direct current stimulation of the right PPC (Roy, Sparing, Fink, & Hesse, 2015). Interestingly, both behavioural and psychophysical evidence in both adults and children reported larger cuing effects in participants with DD, mainly for targets presented in the left hemifield, suggesting that attentional disengagement deficits are linked to a right parietal dysfunction associated to reading disorders (Facoetti et al., 2006; Hari, Renvall, & Tanskanen, 2001, pp. 1373–1380).

However, a possible role of AVG experience on attentional disengagement mechanisms - controlled by pre-frontal attention areas (Bertoni et al., 2021; Pasqualotto et al., 2022) and fronto-parietal interactions (Bavelier, Achtman, Mani, & Föcker, 2012; Föcker, Mortazavi, Khoe, Hillyard, & Bavelier, 2019) - cannot be completely excluded. Interestingly, the association between AVG playing experience and faster auditory attention (Green et al., 2010) might provide a reasonable explanation as to why AVG training boosts "auditory" phonological skills subtending reading skills (Franceschini & Bertoni, 2019; Franceschini et al., 2013, 2017). Both structural and functional neuroimaging studies have recently demonstrated a large overlap in the right fronto-parietal attentional networks between spatial attention and, lexical as well as sub-lexical, reading (Ekstrand et al., 2020; Ekstrand, Neudorf, Gould, Mickleborough, & Borowsky, 2019; Ekstrand, Neudorf, Kress, & Borowsky, 2019). Lastly, it is important to note that the primary auditory cortex, at the basis of the phonological processing, receives information not only in a top-down manner from the PPC and from other multisensory areas (prefrontal cortex and superior temporal polysensory area), but also from lateral projections from primary and secondary visual cortices as well as from feedforward inputs from nonspecific and higher order thalamic regions (e.g., suprageniculate, posterior, anterior dorsal and magnocellular divisions of the medial geniculate complex, and portions of the pulvinar complex) (Schroeder, Lakatos, Kajikawa, Partan, & Puce, 2008).

Although our data cannot disentangle which changes in the brain led to reduced cuing effects associated with AVG experience, it still suggests that these changes might have had a positive transfer into the reading domain. Accordingly, AVG players demonstrated better phonological decoding and phonological working memory skills than non-players, reflected by higher accuracy in the pseudoword text reading task and in the BSR task. This benefit in the AVG group was found despite the absence of group difference on typical text reading tasks (text reading with and without comprehension), confirming that both groups were composed of skilled adult readers. It is noteworthy that the benefits observed for the AVG group were restricted to some of the most phonologically demanding tasks. This is in line with previous data showing that variability in reading-related tasks within skilled reader adult players is likely to be greater under challenging conditions (Antzaka et al., 2017), making reading-related benefits more visible in tasks for which a sufficient amount of processing resources is taxed.

Accordingly, it has been shown that AVG training boosted phonological decoding skills in children with DD (Bertoni et al., 2019, 2021; Franceschini & Bertoni, 2019; Franceschini et al., 2013, 2017).

In addition, correlation analyses showed that in the AVG group, individuals who performed better in the auditory spatial attentional orienting task (i.e., showed a smaller cuing effect) showed better phonological skills and faster text reading skills. These results are in line with previous studies showing improvements in children with DD on phonological short-term memory (Franceschini & Bertoni, 2019; Franceschini et al., 2017) and phonological decoding (Bertoni et al., 2019, 2021; Franceschini & Bertoni, 2019; Franceschini et al., 2013, 2017) tasks after AVG training.

Altogether these results indicate that faster auditory attentional disengagement could be the factor mediating the link between AVG playing and phonological improvements (Franceschini & Bertoni, 2019; Franceschini et al., 2017), and are in line with proposals suggesting a potential causal role of auditory attention in the development of phonological skills (Facoetti et al., 2005; Facoetti, Lorusso, et al., 2003; Hari & Renvall, 2001; Lallier, Donnadieu, et al., 2010; Lallier, Donnadieu, & Valdois, 2013, 2009; Lallier, Tainturier, et al., 2010). In line with the SAS theory (Hari & Renvall, 2001), we suggest that a boost in auditory automatic attention skills resulting from playing AVGs may have benefited, and refined phoneme discrimination processes involved in phonological processing implicated in reading.

One possible explanation for the significant correlations observed within the AVG group only may relate to a more frequent – hence more trained and efficient – access to auditory attentional skills in this group because of frequent AVG playing experiences. We suggest that these attentional skills might be more easily accessible in this group, even when other tasks such as those targeting phonological skills are being performed. For example, when faced with phonological tasks, AVG players may benefit from more “active” and more “available” auditory attentional resources (in addition to phonological and language resources) to boost performance.

5. Conclusions

Overall, the present study provides evidence that playing AVGs is related to better auditory attentional disengagement, more accurate phonological working memory, and phonological decoding performance. Our results challenge the claim that visual attention is the principal component mediating the link between AVG training and reading improvements. Indeed, our results strongly suggest that AVG training might lead to amodal attentional improvements that can be observed in both the visual and auditory – as well as “phonological” - domains. Our study offers new research avenues regarding the use of AVGs as an amodal effective alternative to traditional remediation programs for readers with DD.

Author statement

Martina Mancarella: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

Alexia Antzaka: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Visualization; Writing - original draft; Writing - review & editing.

Sara Bertoni: Conceptualization; Formal analysis; Methodology; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

Andrea Facoetti: Conceptualization; Formal analysis; Methodology; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing; Supervision.

Marie Lallier: Conceptualization; Formal analysis; Methodology; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing; Funding acquisition; Supervision.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chb.2022.107344.

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