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RESEARCH ARTICLE

Playing Super Mario increases oculomotor inhibition and frontal eye field grey matter in older adults

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Abstract
Aging is associated with cognitive decline and decreased capacity to inhibit distracting information. Video game training holds promise to increase inhibitory mechanisms in older adults. In the current study, we tested the impact of 3D-platform video game training on performance in an antisaccade task and on related changes in grey matter within the frontal eye fields (FEFs) of older adults. An experimental group (VID group) engaged in 3D-platform video game training over a period of 6 months, while an active control group was trained on piano lessons (MUS group), and a no-contact control group did not participate in any intervention (CON group). Increased performance in oculomotor inhibition, as measured by the antisaccade task, and increased grey matter in the right FEF was observed uniquely in the VID group. These results demonstrate that 3D-platform video game training can improve inhibitory control known to decline with age.

Keywords Frontal eye fields · Attention · Antisaccade · Cognitive training · Video game · Ageing

Introduction

Aging is associated with cognitive decline and deficits in executive function present as one of the earliest cognitive domains to be affected. Executive function can be assessed by tasks that measure cognitive control, task-switching and the inhibiting of distracting information not relevant to the goal at hand (Miller 2000; Winocur et al. 2007). Inhibitory control is particularly affected by the aging process. Specifically, several studies have shown that older adults have lower performance compared to young adults on tasks that assess the ability to inhibit an automatic, irrelevant response (Andres and Van der Linden 2000; Hasher et al. 1999; Wecker et al. 2000). The antisaccade task, during which the subject must make a saccade in the opposite direction of a presented target, is one well known task that measures this form of inhibitory control (Hallett 1978). To properly execute an antisaccade, the reflexive saccade must be inhibited before initiating the voluntary saccade (Everling and Fischer 1998). The percentage of correct antisaccade responses declines with age (Olincy et al. 1997; Sweeney et al. 2001) because older adults have more difficulty inhibiting reflexive saccades before initiating a goal-directed saccade to its intended location (Bowling et al. 2012; Butler et al. 1999; Nieuwenhuis et al. 2000). This difficulty may be related to changes in cognitive functions related to attention (Nieuwenhuis et al. 2004) and has been generally considered as an indicator of decline in age-related inhibitory control (Butler et al. 1999). Importantly, the antisaccade task has been established as a reliable measure of inhibitory control that is associated with the integrity of neural structures supporting executive function in older adults particularly in the frontal eye fields (FEFs)(Mirsky et al. 2011). The latter is involved in the suppression of automatic responses and in the generation of goal-directed saccades, which is an important role in the antisaccade task (Munoz and Everling 2004). An incorrect antisaccade (making a saccade towards

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the target) is the result of a lack of inhibition from saccade neurons in the FEF and superior colliculus before the target appears (Munoz and Everling 2004). Inhibition is, therefore, critical for the reflexive saccade to be eliminated in antisaccade trials. Further, lower grey matter in the right FEF is associated with worse antisaccadic performance, providing incremental support for the idea that the right FEF plays a central role in antisaccadic inhibition (Boxer et al. 2012). Bilateral involvement of the FEFs have also been shown to contribute antisaccadic performance (Ettinger et al. 2005).

Inhibitory control as measured by the antisaccade task is also observed in neuropathology associated with ageing. For example, Parkinson's Disease patients display reduced antisaccade performance (Antoniades et al. 2015) which is improved with medication that delivers dopamine agonists targeting frontal structures (Hood et al. 2007). The antisaccade task has also been used shown to be a reliable marker declining executive function in both mild cognitive impairment (Hellmuth et al. 2012) and Alzheimer's Disease patients (Crawford et al. 2005; Kaufman et al. 2012; see Hutton and Ettinger (2006) for review). Decreased antisaccadic performance in older adults, therefore, presents as a known correlate of neurodegenerative disorder in older adults and, therefore, efforts to improve antisaccadic inhibition are of particular interest.

Antisaccadic performance relies on visual, oculomotor and inhibitory mechanisms. Related to this, video game experience has been previously shown to improve cognitive performance within a number of domains in younger adults, including visual attention (Castel et al. 2005; Feng et al. 2007; Green and Bavelier 2003, 2007; West et al. 2015, 2008), oculomotor control (Gozli et al. 2014; West et al. 2013) and executive function (Basak et al. 2008). At this point, limited evidence exists demonstrating the effects of video game training on neural structures supporting oculomotor control and executive function in older adults; however, behavioral studies have shown an impact of video game training on cognitive performance within this population. For example, Basak, Boot, Voss and Kramer (2008) had older adults train for 23.5 h on a real-time strategy game and found a significant post-training improvement in performance in executive function and visual short-term memory performance compared to a passive control group. Further, it was found that older adults who trained on a custom made video game displayed reduced multitasking costs and improved sustained attention and working memory function (Anguera et al. 2013). Following this lead, cognitive interventions using video games have emerged as a potentially effective tool to mitigate cognitive decline in older adults. In particular, an intervention using a video game has the potential to improve oculomotor and inhibitory control in older adults due to in-game demands that ask the player to continually direct eye movements towards goal-relevant information while effectively inhibiting an abundance of non-relevant environmental information. Mastering this type of cognitive control is thought to be necessary to effectively progress through a game's increasingly difficult stages.

We recently found that playing 3D-platform video games, such as Super Mario 64, was causally linked to increased grey matter in the hippocampus in both younger (West et al. 2017a, b) and older adults (West et al. 2017a, b). In both studies, a longitudinal training design was employed to measure the impact of video game training on the hippocampus. In the present study, we used the same sample of older adults from West et al. (2017a, b) to investigate the effectiveness of a video game to improve inhibitory control in older adults as measured by the antisaccadic task. We chose the game Super Mario 64, due to previous evidence showing that playing is related to increased grey matter in frontal structures, including the right dorsolateral prefrontal cortex (DLPF), in younger adults (Kühn et al. 2014; West et al. 2017a, b). Super Mario 64 contains a series of visuospatial tasks that requires players to effectively inhibit distracting non-goal related information to direct actions towards in-game goals. For example, while searching for in-game tokens needed to progress through the game (e.g., coins and stars), a player must quickly direct eye movements back and forth between regions that contain tokens and regions that contain enemies and obstacles. When eye movements are directed to one game aspect (e.g. enemies), other concurrent aspects need to be effectively inhibited (e.g., location of tokens) to successfully maneuver the character through the game's environment. Thus, we count on the fact that the in-game requests eliciting the DLPF cortex, including the FEF, will result in plasticity process of these structures. Accordingly, our goal was to improve antisaccadic inhibition through Super Mario 64 training, and we expect that this improvement will be related to an increase of grey matter in the right FEF, which supports oculomotor inhibition as measured in the antisaccade task (Hellmuth et al. 2012; Mirsky et al. 2011; Olincy et al. 1997; Sweeney et al. 2001). In short, we hypothesize that Super Mario 64 training will increase inhibition performance, which we will test with a behavioral primary outcome measure: the antisaccade task. Additionally, since grey matter in the FEFs support antisaccadic performance, we will examine changes in this structure as a secondary outcome measure to support our primary measure in the anti-saccade task. To ensure the impact of playing a video game was not related to test-retest effects, or general cognitive improvement due to learning a new skill, we included two control groups that served as a comparison to the group that played Super Mario 64 (VID group). We included an active control group who learned to play the piano for 6 months (MUS group). Piano training was chosen as an active control because it would primarily target cognitive processes related to audition that were not of interest in

this study and contrasted with the visuospatial navigation and attention training associated with a 3D-platform video game. Finally, a passive no-contact control group (CON group) was also included. We predicted that music training would not have an impact on antisaccadic performance due to its lack of a strong dynamic visuospatial component. Similarly, the CON group was also expected to not show an increase in antisaccadic performance. Participants underwent a structural MRI scan during a pre- and post-training testing session. Participants also completed the antisaccade task outside the scanner three times at a pre-, mid- and post-training testing session. Because the antisaccade task was administered three times we also examined the effect of the cognitive treatment "dose" across each testing session. We, therefore, planned two separate analyses: one comparing the pre- and mid-training session and a second comparing the mid- and post-training session.

Materials and methods

Participants and randomization procedure

Participants were recruited into the study from the Centre de recherche de l'Institut universitaire de gériatrie de Montréal participant pool. Participants were pre-screened to ensure that they did not have any present or past major illness, had normal hearing, had normal or corrected to normal vision, did not meet criteria for Mild Cognitive Impairment (MCI), did not take any medication known to have an impact on cognition and were MRI compatible. Further, all participants were non-video game players and non-musicians. The Montreal Cognitive Assessment (MoCA) was used to screen participants for MCI. Only participants with a MoCA score higher than 23 were invited to participate in the study. All participants had a pure-tone average (PTA) for speech frequencies (500, 1000 and 2000 Hz) below 40 dB HL (i.e., normal hearing or mild hearing loss) in their best ear (PTA scores: MUS = 16.4 (SD = 10.5); VID = 10.7 (SD = 6.1); CON = 11.0 (SD = 6.6)). All participants reported having normal vision either with or without glasses.

All participants were randomized into one of the three groups. Randomization was done by an independent research assistant, using a predefined randomization table prior to contacting participants to ensure that they were blind to the existence of the other two conditions. Randomization was stratified using a covariate-adaptive randomization. Each factor was stratified into two categories. For the factor of age there were "younger" (55–64 yrs) and "older" (65–75 yrs); for the factor of education there was low (< 16 yrs) and high (> 16 yrs); and for the factor of gender there was female and male. Because participants were recruited from a database, age, education level, and gender of each participant were known before they were contacted and it was thus possible to stratify randomization on the basis of these three factors.

To reduce the impact of expectancy on test–retest effects, all participants were told that they were part of an experimental group. Participants in the VID group were told that there was evidence that video game training can enhance cognitive abilities, and that video game training in older adults is expected to improve those abilities. Participants in the MUS group were told that there was evidence that musicians have enhanced cognitive abilities, and that we expected musical training to improve those abilities. Finally, the CON group was told that we were investigating test–retest effects, and that they were expected to improve on all tasks. All participants were debriefed about the other groups at the end of the final testing session.

Forty-nine participants in total were recruited into the study. Using the stratified randomization procedure, 15 participants were assigned to the VID group, 14 participants were assigned to the MUS group and 15 participants were assigned to the CON group. During the study, 2 participants withdrew from the MUS group, 2 withdrew from the CON group, while 11 withdrew from the VID group. To account for the higher attrition rate within the VID group, an additional five participants were assigned who were matched for the age, gender and education of the other two groups, however, the stratified randomization procedure was not used in these cases. Further, one additional participant in the VID group dropped out of the study between the mid- and post-training sessions. This resulted in a total of 9 participants completing the training within the VID group for the pre- and mid-training sessions and a total of 8 participants completing the post-training session. The demographics of the participants within each group are presented in Table 1. The study received ethical approval from the Comite conjoint d'evaluation scientifique–Regroupment Neuroimagerie/Quebec (CES-RNQ).

To ensure that the groups are equivalent and that no participant meet the criteria for MCI, we used the Montreal Cognitive Assessment (MoCA). The MoCA is a brief sensitive screening tool generally used to discriminate against individuals with mild cognitive complaints (Nasreddine et al. 2005).

Table 1 Demographic information for each experimental group

	Age (+/− SD)	Education (+/− SD)	Gender (% of females) (%)	Final *n*
VID Group	69.3 (5.7)	15.2 (3.2)	55.5	8
MUS Group	67.7 (4.3)	14.7 (2.3)	83.3	12
CON Group	66.9 (3.9)	17.5 (2.3)	76.9	13

Training procedure

Participants in both training groups were asked to train for a minimum of 5 days a week for 30 min each day, but were told that they could train for longer periods of time if they desired. Participants recorded their daily training time on a log sheet provided by the experimenter that was collected at the end of the experiment. An experimenter also contacted the participant once per month to gauge training progress and to ensure that the log sheet was being filled out correctly. Otherwise there was no additional contact with participants after the initial set up and introductory training sessions (see below for full procedure). No training data from the home computers/gaming system was available. Participants in both training groups were treated identically and had equal contract with the experimenter after the training sessions were given. The specific training procedure for the VID and MUS group is as follows.

Video game training (VID group)

Video game training was done at home using the Nintendo Wii console system equipped with a Wii Classic Controller. Participants trained on Super Mario 64. Once a participant completed the pre-tests, a research assistant installed the Nintendo Wii at the participant's home. The research assistant then gave an initial orientation to the participant to teach them how to turn on the Nintendo Wii and access the Super Mario 64 game. This was then followed by an in-game orientation that taught the participant to move the character around the virtual environment. Some participants had certain challenges associated with maneuvering the character at this point. Issues included a difficulty with understanding the game's mechanics and poor motor coordination. Super Mario 64 has a steep learning curve that was not originally designed to be played by someone with little to no video game or computer experience. We, therefore, provided the participant up to three additional supervised 2 h training sessions with a research assistant to teach the participant how to properly maneuver the character and progress through the game. All participants in the VID group completed 2–3 additional training sessions lasting 2 h. Once completed, participants were given a custom instruction booklet which outlined how and where to collect all the stars for the first four levels. This allowed participants to learn the game's mechanics in further detail and practice the basic motor coordination needed. After this point, participants had to search for and obtain the stars within each remaining level without any assistance. Two participants completed all task within Super Mario 64 before the completion of the 6 months training period. They, therefore, continued to train on a similar game, Super Mario Galaxy, until the end of the training period. Super Mario 64 and Super Mario Galaxy are both three-dimensional platform games where the player is tasked with exploring a virtual environment to search for stars (tokens). Once enough stars are collected through completing in-game tasks, the player will progress further into the game's levels and will access new environments to navigate through and explore.

Piano training (MUS group/Active Control)

Piano training was done at home using Synthesia software, and an 88-key M-Audio MIDI piano. A research assistant installed and calibrated the piano to work on the participant's home computer. They then participated in an introductory lesson that included basic information about music, detailed instructions on how to use Synthesia, and directions on how to record their progress. Introductory music information included lessons about note names, how to place hands on the piano, and how to synchronize performance with the information on the screen and the metronome. An introductory lesson with the experimenter was then given to the participant to teach them basic keyboarding skills and concepts. This all lasted 1.5 h total. Participants then were told to continue with the additional lessons independently, which became more and more advanced (e.g., chords, flats, sharps, finger placement, higher tempo, etc.). At the end of each lesson the participant is given a performance score out of 100. Participants were instructed to continue to the next lesson once they achieved a score of at least 80/100. There was a total of 65 lessons available. Participants were told to move at their own pace, but to try to master a given lesson or song before moving on and did so independently.

Passive control group

The passive control group did not have any contact with the research team with the exception of the pre- mid- and post-training sessions.

Outcome measures

A structural MRI scan was administered at the pre- and post-training session. Participants also completed the antisaccade task outside the scanner at the pre-, mid- and post-training testing session.

Antisaccade task

Saccadic eye movements were recorded by measuring pupil position and corneal reflectance using a camera-based eye tracker (SR Research Eyelink 1000) with a temporal resolution of 1000 Hz and a RMS spatial resolution of 0.01° of visual angle. Gaze position was established using a nine-point calibration and validation scheme. The beginning and

the end of saccadic eye movements were determined using a 30°/s threshold with the additional criterion that the eye exceeded an acceleration of 8000°/s/s during the movement. Experimental displays were presented on a 21 in. flat CRT at a refresh rate of 85 Hz and a resolution of 1024 × 768 pixels. A chin rest was used to fix the head of the participants 80 cm from the monitor. Each experimental session began with eye-tracker setup during which calibration and validation were performed repeatedly until a minimum average accuracy of 0.5° was attained.

The task included both prosaccade trials (saccades directed towards the target) and antisaccade trials (saccades directed in the opposite direction of the target). Participants completed a block of 6 practice trials in the prosaccade condition and a block of 6 practice trials in the antisaccade condition. Participants then completed 10 blocks, each consisting of 16 experimental trials. They were given self-timed breaks between blocks. The experimental condition of the blocks alternated between prosaccade and antisaccade trials which were counterbalanced. This resulted in participants completing a total of 80 prosaccade and 80 antisaccade trials. Trials with a saccadic reaction time lower than 100 ms or higher than 900 ms were excluded from analysis, resulting in 91% of trials included in analysis.

The trial sequence is depicted in Fig. 1. Every trial began with a fixation stimulus (a white ring with an outer diameter of 0.35° and an inner diameter of 0.16°) that was presented in the center of the display on a light-grey background. Once participants moved their gaze to within 1.5° of the fixation stimulus, they were required to maintain fixation within this region for a randomly determined duration between 800 and 1300 ms. After this, a target consisting of a black square (subtending 2.0° × 2.0°) was presented 10° from fixation. The target was presented either to the left of right of fixation 50% of the time. In the prosaccade blocks, the participant was instructed to make a saccade towards the target. Errors were calculated as saccades that ended outside of a circular interest window that surrounded the target by 4.0°. In the antisaccade blocks, participants were instructed to make a saccade in the opposite direction of the presented target. Errors were calculated as saccades that were made towards the side that the target occupied. Correct trials were calculated as saccades that arrived at least 3° to the side of fixation opposite the target. Saccadic reaction times and accuracy were collected dependent measures.

Voxel-based morphometry

Participants were scanned on a Siemens TIM Trio 3T MRI system (Siemens Medical Solutions, Erlangen, Germany), using the Siemens 12-channel receive-only head coil at L'Unité de Neuroimagerie Fonctionnelle (UNF) of the Centre de recherche de l'Institut universitaire de gériatrie de Montréal. An MPRAGE anatomical scan of approximately nine minutes was performed. A three-dimensional gradient echo acquisition was used to collect 160 contiguous 1 mm *T*1-weighted images in the sagittal plane (TR = 2300 ms, TE = 2.91 ms, flip angle = 9°, FOV = 256 mm^2, voxel size = 1 mm × 1 mm × 1 mm resolution).

Changes in grey matter were measured using voxel-based morphometry (VBM). VBM is a computational approach to neuroanatomy that measures differences in the local density of brain tissue through a voxel-wise comparison of multiple brain images (Ashburner and Friston 2000). MRI images were run through a bioinformatics pipeline (bpipe). The images were first corrected for intensity non-uniformity (shading artifacts) using the N4 software package (Sadedin et al. 2012) and then spatially normalized by linear transformation using ICBM 152 atlases (Yoon et al. 2009). The neck was then removed from the scans using a head mask of the brain with open-source MINC tools (http://www.bic.mni.mcgill.ca/ServicesSoftware/MINC). The BEAST algorithm was used to linearly normalize the intensity of scans, masked individually using a brain mask generated in model space (Eskildsen et al. 2012). Intensity Normalized Stereotaxic Environment for the Classification of Tissues (INSECT) (Filippi et al. 1998) was used to automatically label voxels as white matter, grey matter, cerebrospinal fluid, or background. White matter, grey matter, and cerebrospinal fluid were extracted from the brain and blurred using a 4 mm FWHM (full-width at half-max) Gaussian kernel. Analyses were run using RMINC (http://launchpad.net/rminc), which operates using the R statistical package (http://www.r-project.org).

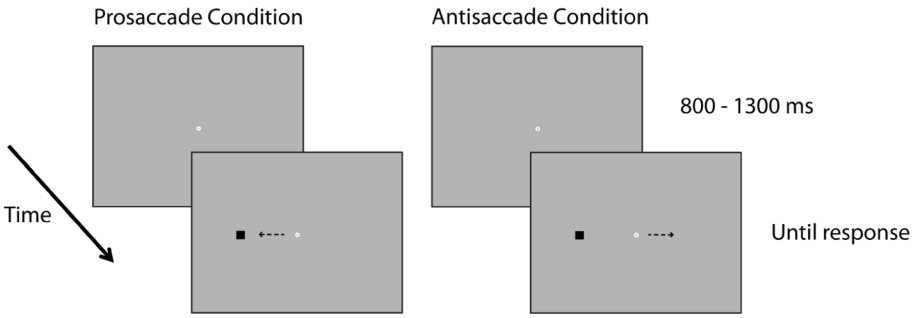

Fig. 1 A typical trial sequence in the antisaccade paradigm. In the prosaccade condition, participants were instructed to make a saccade towards the target. In the antisaccade condition participants were instructed to make a saccade towards the side contralateral to the target

Data analysis

Antisaccade task

The prosaccade and antisaccade conditions were treated as two separate dependent measures. For both dependent measures, reaction time and accuracy scores were submitted to two separate omnibus ANOVAs that examined the factors of Time (Pre-, mid- and post-training) and Group (VID; MUS; CON) and their interaction. In addition, for each dependent measure we planned separate a priori ANOVAs that examined performance changes between the pre- and mid training and between mid- and post-training. Due to our a priory hypothesis, we also planned within-group and between group comparison using *t*-tests to asses changes in performance defined as either a change in reaction time or accuracy scores between testing sessions. All statistical tests were set at threshold of $p < .05$.

Voxel-based morphometry

A planned paired sample *t* test was conducted for each training group to investigate changes in grey matter between pre- and post-training. Based on our a priori hypothesis, an uncorrected threshold of $p < .001$ for the peak voxel within our region of interest (ROI) was set (Bohbot et al. 2007; Iaria et al. 2003; Konishi and Bohbot 2013; West et al. 2017a, b), namely the FEFs. For the rest of the brain, a threshold of $p < .05$ corrected for multiple comparisons using a Bonferroni correction was used. Output images are displayed on a group average MRI scan.

Note

A number of additional measurements were taken to examine the impact of music training on auditory cognition. The purpose of this paper, however, is to report the benefits of video-game playing on oculomotor inhibition and related neural structures. Results related to the benefits of music training on audition will be reported elsewhere.

Results

No participant who completed the training and post-tests were removed from analysis for any reason.

Equivalency of groups at pre-test

Due to the higher attrition rate within the VID group we tested if there were any group differences in grey matter at pre-test within our a priori defined ROI. This was due to the fact that there might have been a selection bias where cognitively healthier people within the VID group chose to stay in the study. This analysis revealed no significant group differences at pre-test within the FEFs, even at a more liberal uncorrected threshold of $p < .05$. Group pre-test equivalency was further confirmed when examining pre-test MoCA scores using a one-way ANOVA (CON Group: 26.61 (SD = 2.14); MUS Group: 28.16 (SD = 1.99); VID Group 26.93 (SD = 1.32); $F(2,30) = 2.18$, $p > .1$). Planned comparisons also revealed no significant MoCA differences ($ts < 1$). We compared performance between groups using one-way ANOVAs on the antisaccade task at pre-test. This revealed no significant group differences in either prosaccade or antisaccade performance as measured by reaction time and accuracy scores (all $ps > 0.3$).

Training performance

Participants in the VID group trained for an average of 72 h (SD = 11.3; range = 52–149; median = 83 h) and collected an average number of 69 Star/Shine tokens (SD = 13.52), which correlated with hours of training ($r(7) = 0.78$, $p < .05$).

Participants in the MUS group trained for an average of 83 h (SD = 34.3; range = 58–89; median = 69 h), and completed an average of 30 piano lessons (SD = 14.2) with a minimum score of 80/100. This also correlated with total hours trained ($r(11) = 0.82$, $p < .001$).

Antisaccade performance

Data for both prosaccade and antisaccade conditions can be seen in Table 2. We first examined the accuracy scores in the antisaccade condition. The groups were not significantly different at pre-test ($F(2,32) = 1.17$; p = .321). A Time (pre-; mid-; post-training) × Group (VID; MUS; CON) repeated measures ANOVA was first conducted. A main effect of Time was observed ($F(2,58) = 3.27$, $p < .05$; $\eta^2 = 0.101$) while not main effect of Group was observed ($F = 1.01$). A Time × Group interaction was marginally significant ($F(4,58) = 2.70$, $p = .068$; $\eta^2 = 0.135$). We next conducted planned ANOVAs to further measure the effect of training dose by examining performance change at 3 months of training (pre- to mid-training session) and at the full 6 months of training (mid- to post-training session). To accomplish this, we conducted two separate planned repeated measures ANOVAs using a mixed factorial design with Time as the within-subject factor and Group (VID; MUS; CON) as the between-subject factor. The first ANOVA comparing the pre- and mid-sessions revealed a significant effect of Time ($F(1,31) = 7.94$, $p < .01$; $\eta^2 = 0.204$) and a significant Time × Group interaction ($F(2,31) = 4.59$, $p < .05$; $\eta^2 = 0.228$). Planned within-group comparisons using *t*-tests comparing performance at pre- and mid-sessions were conducted to identify which training group was driving the

Table 2 Pro- and antisaccade results by group and time

	Prosaccade accuracy (%; +/− SD)			Prosaccade RT (+/−SD)			Antisaccade accuracy (+/− SD)			Antisaccade RT (+/− SD)		
Time	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3
VID Group	93% (5)	94% (4)	93% (8)	181 ms (40)	203 ms (42)	204 ms (26)	22% (19)	41% (18)	44% (20)	350 ms (120)	358 ms (48)	325 ms (55)
MUS Group	95% (3)	95% (4)	96% (5)	194 ms (29)	205 ms (45)	199 ms (34)	32% (23)	29% (22)	35% (23)	339 ms (81)	362 ms (112)	346 ms (95)
CON Group	93% (5)	96% (5)	93% (6)	189 ms (38)	186 ms (36)	179 ms (40)	22% (17)	29% (22)	26% (24)	372 ms (105)	362 ms (77)	374 ms (65)

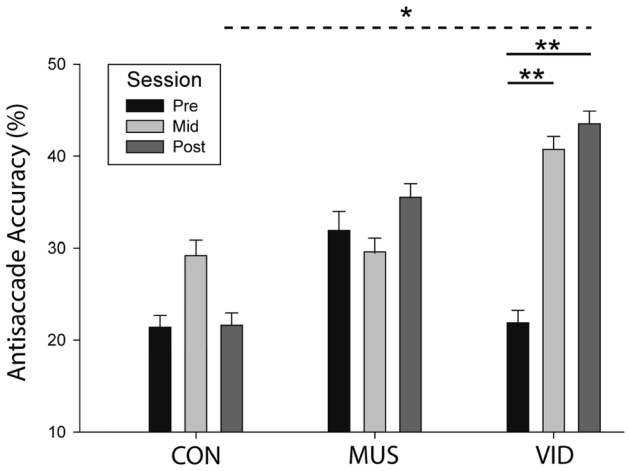

Fig. 2 Antisaccade accuracy (inhibition performance) for each session (pre-, mid- and post-training) and group (*CON* control group, *MUS* music hroup, *VID* 3D-platform video game group). *$p < .05$, **$p < .01$; +/− standard error

observed interaction. This revealed a significant performance increase in accuracy from the pre-training session to the mid-training session that was specific to the VID group (pre-training: 21.9%; mid-training: 40.8%; $t(9) = 4.41$, $p < .01$; $d = 1.402$; Fig. 2). No significant increase was observed in the MUS group ($p = .64$) or the CON group ($p = .19$). The subsequent ANOVA comparing mid- and post-training session revealed no significant effect of Time or Time × Group interaction (Fs < 1). Planned within-group comparisons examining performance changes in accuracy between the pre-training and post-session sessions reveled a further significant difference in the VID group (pre-training: 21.7%; post-training:43.6%; $t(7) = 3.41$, $p < .01$; $d = 1.303$). Planned between-group comparisons were also conducted at each time (pre-; mid-; post-training). This revealed a significant group difference between the CON (21.6%) and VID group at post-test (43.6%; $t(18) = 2.13$, $p < .05$; $d = 0.984$).

We next submitted prosaccade accuracy scores to a Time (pre-; mid-; post-training) × Group (VID; MUS; CON) repeated measures ANOVA. No significant effect were found (all Fs < 1).

Prosaccade and antisaccade reaction time data were each submitted to a separate Time (pre-; mid-; post-training) × Group (VID; MUS; CON) repeated measures ANOVA. No significant results were revealed (all Fs < 1).

Voxel-based morphometry

We next tested for training related changes in grey matter within the FEFs by comparing MRI scans collected at pre- and post-training. In the VID group, there was a significant increase in grey matter in the right FEF ($x = 25$, $y = -8$, $z = 48$; $t = 6.65$, $p < .0005$; $d = 2.122$; Fig. 3). Grey matter

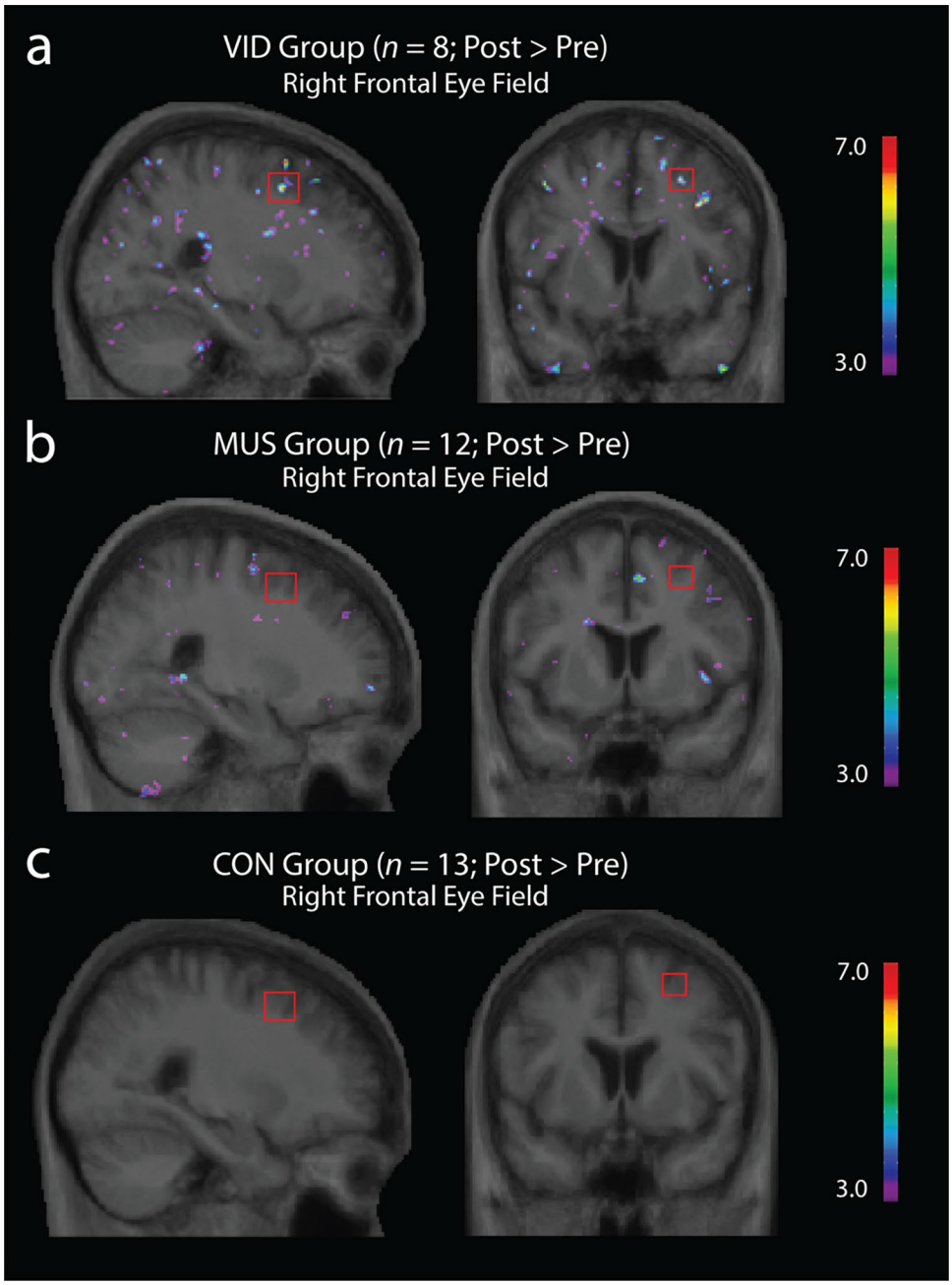

Fig. 3 Result of the VBM analyses. The data are not masked. Analyses were uniquely performed on grey matter, however, the statistical maps are overlaid on the average sample *T*1 image that contain both grey and white matter. **a** Increased grey matter in the right Frontal Eye Field (FEF) after 6 months of 3D-platform training (VID). **b** No significant increase in FEF grey matter was observed after 6 months of music training (MUS) or in (**c**) the passive control group (CON)

values at the peak voxel of the significant cluster were also submitted to a Time (pre-; post-training) × Group (VID; MUS; CON) repeated measures ANOVA which revealed a significant Time × Group interaction (F (2.30) = 6.633, $p < .001$, $\eta^2 = 0.307$). No significant within-group increases in FEF grey matter were observed in either the MUS or CON group. We then examined the relationship between training related changes in grey matter within the peak significant voxel of the right FEF and change in antisaccadic accuracy performance. This revealed a significant correlation where change in grey matter in the right FEF was related to change in antisaccadic performance ($r_{(32)} = 0.494$, $p < .01$; Fig. 4).

When conducting a whole brain analysis outside our ROI at a threshold of $p = .05$ corrected for multiple comparisons, we did not observe any other significant grey matter changes.

Discussion

We investigated the impact of 3D-platform video game training on the inhibitory function of older adults using the antisaccade task. The production of antisaccades are supported by a cortical inhibitory network that include the FEF (Mirsky et al. 2011) and antisaccadic performance is correlated

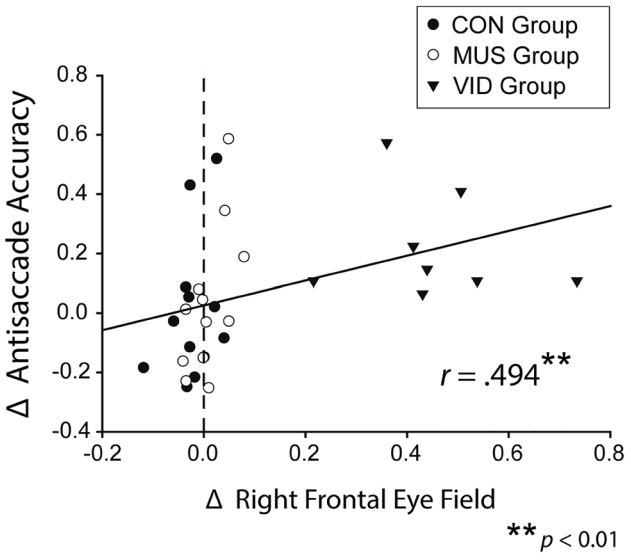

Fig. 4 Increased antisaccade inhibition performance was correlated with increased grey matter in the right frontal eye field (FEF) at post-training. Closed circles represent the CON group, open circles represent the MUS group and triangles represent the VID group

with grey matter within the FEF (Boxer et al. 2012). We assumed that playing super Mario 64 would improve inhibitory control by increasing grey matter in frontal structure, as suggested in previous studies (Kühn et al. 2014; West et al. 2017a, b). The increase in grey matter should have an impact on antisaccade task performance. Indeed, older adults in the VID group showed increased inhibition performance at post-training supported by an increased grey matter in the right FEF. Further, when examining the entire sample change in antisaccadic performance at post-training was related to change in grey matter within the right FEF, however, this effect was driven by the VID group. The active control MUS group was not associated with a significant increase in either antisaccadic inhibition or an increase in grey matter within the FEFs compared to the passive control CON group, nor was any within-group improvement observed. Similarly, the CON group, who received no training, displayed no significant performance improvement. As predicted, Super Mario 64 training improved antisaccadic inhibition and this improvement was associated with an increase in grey matter in the right FEF. These results suggest that frontal inhibitory processes can be improved in older adults by training on a 3D-platform video game. Specifically, accuracy enhanced after 3D-platform game training when making a saccade to the opposite side of the displayed target. In addition, improved accuracy was observed after a 3 months dose of training and performance remained stable at 6 months post-training. This demonstrates that 3D-platform video game training has the ability to improve inhibitory processes known to decline with age after as little as 3 months of training (Bowling et al. 2012; Butler et al. 1999; Nieuwenhuis et al. 2000; Olincy et al. 1997; Sweeney et al. 2001).

Antisaccadic performance has been shown to strongly correlate with neuropsychological tests of executive function in older adults. Indeed, Mirsky et al. (2011) showed that antisaccadic accuracy (measured by the percentage of correct answers) was associated with measures of executive function and also correlated with the volume of grey matter in frontal brain regions that included the FEFs and the Supplementary Eye Fields. In the current study, we only observed a significant post-training increase in the right FEF, which is centrally implicated in oculomotor inhibition (Boxer et al. 2012; Munoz and Everling 2004).

The increased inhibitory control observed in older adults after video game training supports previous findings observed in younger adults related to executive function. For example, it was found that action video game training increased dual-task and task switching performance (Strobach et al. 2012). Further, experienced video game players display enhanced top-down oculomotor control (Chisholm and Kingstone 2012; West et al. 2013). In older adults, video game training has previously been shown to improve executive function as measured by the Raven's Progressive Matrices test (Basak et al. 2008). Our results extend these finding to demonstrate that video game training in older adults can also improve oculomotor inhibition and increase grey matter in the right FEF.

Our data, therefore, could be characterized as demonstrating a transfer effect. Transfer occurs when the development of knowledge, skill or competence in one area affects learning or performance in another area of competence (Cormier and Hagman 2014). It is noteworthy that tasks that people competed within Super Mario 64 during training were not very similar to the experimental antisaccade task. It is likely that the different in-game tasks recruit the same overlapping mechanisms that support inhibitory control. In addition, the demonstration that video game playing can improve oculomotor inhibition in the antisaccade task suggests that this type of training could transfer to improvement of function in everyday task. For example, driving is a complex task which requires the effective, continuous allocation of attention towards objects and events on the road while effectively inhibiting items that are not relevant to the task at hand. It is, therefore, possible that the increased executive function displayed in older adults after 3D-platform video game training could transfer to improved performance in real life tasks, such as driving, where performance tends to decline with age (Wolfe and Lehockey 2016). It is also possible that 3D-platform training would result in increased performance in tasks that rely on effective frontal inhibition and decline with age such as planning and navigation. Future research should specifically investigate the impact of video game

training on older adults' performance in real world tasks. With respect to using 3D-platform video games to train executive function in older adults, future research is needed to confirm if improvement in inhibitory control by way of training transfers to improvement in other forms of executive function (e.g., task-switching, planning).

A limitation of the current results is that the attrition rate was much higher in the VID group compared to the other groups. This may suggest that training on a 3D-platform game was more challenging for older adults compared to music training. One reason for this challenge is the increased difficulty that occurs early within Super Mario 64 coupled with the requirement to learn complex motor commands that are needed to progress successfully through the game. While piano playing was also new to participants within the MUS group, piano playing was likely more familiar to the participants in this group. Older adults have likely seen people play piano throughout their lives while at the same time they are much less familiar with video game playing. Kuhn et al. (2014) noticed that improvements appeared to be moderated by participant's appreciation of video games. We may deduce that the higher attrition rate in the VID group might be related to the video game enjoyment. Besides, it is not inconsistent with the previous idea: a more challenging demand could affect the pleasure of playing. The present results, therefore, represent a proof of concept that supports the development of a video game training tool that is more specifically tailored for older adults. This would require a more gradual increase in difficulty and simpler motor commands while preserving the other aspects of a 3D-platform game's design. Alternatively, it is likely that future cohorts of older adults will be more familiar and comfortable with video game playing, and thus using commercially available video games may be more viable for older adults in the future.

Aging is accompanied by reduction in the volume of grey matter and cerebral cortex. Inhibitory control and executive functions are particularly affected by these changes. Subsequent experiments have shown that video games can increase cognitive performance (Anguera et al. 2013; Basak et al. 2008). More specifically, 3D platform video games can improve grey matter in frontal structure in younger adults (Kühn et al. 2014). Our current results are the first to show that 3D-platform video game training can improve inhibitory control in older adults. Future research should focus on the longevity of these observed effects, transfer to cognitive performance related to other forms of executive function, and the development of game centered training tools specifically tailored for older adults.

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