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Age Moderates the Association of Aerobic Exercise with Initial Learning of an Online Task Requiring Cognitive Control

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Abstract

The aim of this study was to examine whether people differed in change in performance across the first five blocks of an online flanker task and whether those trajectories of change were associated with self-reported aerobic or resistance exercise frequency according to age. A total of 8752 men and women aged 13–89 completed a lifestyle survey and five 45-s games (each game was a block of ~46 trials) of an online flanker task. Accuracy of the congruent and incongruent flanker stimuli was analyzed using latent class and growth curve modeling adjusting for time between blocks, whether the blocks occurred on the same or different days, education, smoking, sleep, caffeinated coffee and tea use, and Lumosity training status ("free play" or part of a "daily brain workout"). Aerobic and resistance exercise were unrelated to first block accuracies. For the more cognitively demanding incongruent flanker stimuli, aerobic activity was positively related to the linear increase in accuracy [B = 0.577%, 95% confidence interval (CI), 0.112 to 1.25 per day above the weekly mean of 2.8 days] and inversely related to the quadratic deceleration of accuracy gains (B = –0.619% CI, –1.117 to –0.121 per day). An interaction of aerobic activity with age indicated that active participants younger than age 45 had a larger linear increase and a smaller quadratic deceleration compared to other participants. Age moderates the association between self-reported aerobic, but not self-reported resistance, exercise and changes in cognitive control that occur with practice during incongruent presentations across five blocks of a 45-s online, flanker task. (*JINS*, 2015, *21*, 802–815)

Keywords: Attention, Executive function, Flanker, Practice effects, Resistance exercise, Memory

INTRODUCTION

Aerobic exercise appears to benefit cognitive function in children (Erickson et al., 2004; Fedewa & Ahn, 2011; Lees & Hopkins, 2013; Sibley & Etnier, 2003; Tomporowski, Davis, Miller, & Naglieri, 2008) and healthy older adults (Bherer, Erickson, & Liu-Ambrose, 2013; Kramer, Erickson, & Colcombe, 2006). Epidemiological evidence from children regarding exercise and cognitive function is unavailable, but case-control (Geda et al., 2010) and prospective cohort (Flicker et al., 2005; Weuve et al., 2004) studies of older adults suggest that aerobic physical activity delays age-related cognitive decline (Haskell, 2008; Sofi et al., 2011), loss of gray matter volume in the prefrontal cortex (Erickson et al., 2010; Rovio et al., 2010) and neurodegenerative disease (Hamer & Chida, 2009), while also reducing mortality risk (Samitz, Egger, & Zwahlen, 2011). Physical inactivity in the teen years has been related to cognitive problems in late life, and this relationship was attenuated by mid-life physical activity (Middleton, Barnes, Lui, & Yaffe, 2010). However, most of the epidemiological studies have examined physical activity and cognitive performance in adults aged 60 and older (Prakash, Voss, Erickson, & Kramer, 2015). Reviewers have pointed out there is inadequate information about the extent to which age moderates the relationship between physical activity and cognition, and that more research is needed about exercise and cognitive function from large samples with a broad age range that better represents the general population (Smith et al., 2010; Snowden et al., 2011).

Whether resistance exercise is effective in delaying declines in cognitive function associated with aging or promotes better cognitive function at younger ages is unclear based on the epidemiological evidence. In randomized trials conducted with older adults, resistance training added to short-term aerobic exercise training led to larger

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improvements in cognitive performance when compared to aerobic training alone (Colcombe & Kramer, 2003). At least seven randomized trials show that short-term resistance training alone improved cognitive performance (Busse et al., 2008; Cassilhas et al., 2007; Lachman, Neupert, Bertrand, & Jette, 2006; Liu-Ambrose & Donaldson, 2009; Moul, Goldman, & Warren, 1995; Peig-Chiello, Perrig, Ehrsam, Staehelin, & Krings, 1998; Tsutsumi, Don, Zaichkowsky, & Delizonna, 1997). In the most recent experiment of this type, the participants were presented with four possible stimuli (60 total in 3 blocks of 20), either a single digit (1 or 3) or three digits (111 or 333). Participants were given two instructions that switched during the task: indicate how many digits appeared (1 or 3) or identify the number present on the screen (1 or 3). In 40% of the trials, these instructions changed which required a change in cognitive strategy. This short-term randomized trial with older adults showed small, statistically insignificant improvements in task switch time and accuracy after resistance training, in part because similar improvements occurred in the health education controls (Kimura et al., 2010).

Much of the knowledge about relationships between cognitive function and physical activity or aerobic fitness is based on small, cross-sectional, laboratory studies that in general targeted homogenous samples of older adults, college students or children (Bauermeister & Bunce 2014; Brown et al., 2010; Chodzko-Zajko, 1991; Colcombe et al., 2003; Davis & Cooper, 2011; Elsayed, Ismail, & Young, 1980; Erickson et al., 2009; Etnier, Nowell, Landers, & Sibley, 2006; Hillman, Castelli, & Buck, 2005; Hillman, Kramer, Belopolsky, & Smith, 2006; Van Boxtel et al., 1997; Voss et al., 2011). Results from these investigations, and the available evidence from randomized controlled trials, suggest that physical activity and aerobic fitness are associated with modest improvements in memory, information processing speed and executive function (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008; Colcombe & Kramer, 2003; Smith et al., 2010). These observations are buttressed by rodent experiments and human neuroimaging studies with older adults and children showing that exercise training induced changes in brain anatomy and physiology that could plausibly support better cognitive control (e.g., altered activity in prefrontal and anterior cingulate cortices) (Chaddock-Heyman et al., 2013; Krafft et al., 2014) and memory (e.g., increased hippocampal and medial temporal lobe volumes and enhanced hippocampal dentate gyrus neurogenesis) (Erickson et al., 2011; Pereira et al., 2007; ten Brinke et al., 2014).

There are few population-based studies that have examined the association of physical activity and cognition across a broad range of ages. One study analyzed data from the mobile app *BrainBaseline* (Lee et al., 2012). The participants ($n = 15{,}346$; 34% ≥ 40 years of age) first completed a short practice block on several cognitive tests during which performance feedback was provided. Next, a main test block involving the same cognitive tests was completed, and these results were used for the analysis. High- and low-exercise groups were created from self-reported prior week frequencies of strenuous, moderate and mild intensity exercise bouts lasting 15 min or more. Using statistical models that controlled for gender and level of education as covariates, the high-exercise group showed faster information processing speed compared to the low-exercise group. There was no difference between the two exercise groups on measures of memory or attention (Lee et al., 2012).

Here, we extend prior research by examining associations between cognitive function and both resistance and aerobic exercise in a large ($n = 8752$), heterogeneous group of online game players ages 13 to 89 years. The sample was older (57.6% > 40 years of age) compared to the Lee and colleagues study (Lee et al., 2012). In addition to gender and education level, we controlled for several other putative confounding variables including smoking (Anstey, von Sanden, Salim, & O'Kearney, 2007), caffeinated coffee and tea use (Beydoun et al., 2014; Ritchie et al., 2010), and sleep (Fortier-Brochu, Beaulieu-Bonneau, Ivers, & Morin, 2012). The flanker task was used because physical activity, exercise training, aerobic fitness, and mobility in older adults have been associated with better flanker performance in several studies of small homogeneous samples (Bauermeister & Bunce, 2014; Chaddock-Heyman et al., 2013; Chaddock et al., 2010; Chaddock et al., 2012; Colcombe & Kramer, 2003; Colcombe et al., 2004; Gothe et al., 2014; Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Motl, et al., 2006; Krafft et al., 2014; McAuley, Szabo, et al., 2011; Niemann, Godde, Staudinger, & Voelcker-Rehage, 2014; Pontifex et al., 2014; Voss et al., 2011). The flanker task is a measure of executive function (Denckla, 1996), or cognitive control (Botvinick, Braver, Barch, Carter, & Cohen, 2001), that assesses the ability to selectively attend to relevant information, to ignore irrelevant information and to inhibit incorrect responses (Eriksen & Eriksen, 1974).

A novel feature of the present investigation is the examination of change across five blocks of a 45-s flanker task. Participants in studies of cognitive function often initially complete several practice trials in a single, short practice block to provide familiarization and reduce improvements in performance that result from practicing a task (i.e., practice effects). Subsequent cognitive tests are often presented in blocks (e.g., of 20 to 160 trials) with analyses performed on a criterion measure which averages performance across all the blocks. The practice trials often are not fully analyzed because they are thought to represent error variance. Practice effects, however, have been shown to be potentially important indices of cognitive health. Practice effects decrease with age (Rönnlund, Lövdén, & Nilsson, 2007) and are smaller among people with lower IQ (Rapport, Brines, Theisen, & Axelrod, 1997) or mild cognitive impairment (Howieson et al., 2008; Wilson, Leurgans, Boyle, & Bennett, 2011). Practice effects also appear to have diagnostic utility (Duff et al., 2011; Shuttleworth-Edwards, Radloff, Whitefield-Alexander, Smith, & Horsman, 2014) and can significantly predict prospective changes in cognitive performance in groups at increased risk for cognitive decline (Duff et al., 2010, 2007; Granholm, Link, Fish, Kraemer, & Jeste, 2010; Machulda et al., 2013; Newman et al., 2001; Suchy, Kraybill, & Franchow, 2011). Similarly, analyses for the first block of trials or changes across the primary test blocks typically have not been reported, although the potential usefulness of considering such changes has been recognized for years (Spirduso, 1980). The relationship between regular (i.e., frequent) physical activity and change in performance during the initial practice trials or across repeated blocks of cognitive tasks has rarely been investigated (Herting & Nagel, 2012), and whether age moderates the effect is unknown.

The primary aim of this study was to examine whether people differed in their change in performance across the first five blocks of a flanker task in a large heterogeneous group and whether those trajectories of change were associated with self-reported aerobic or resistance exercise frequency according to age.

METHOD

Study Population

A data set of 10,000 game players who completed the 45-s *Lost in Migration* game 5 times between January 1, 2012, and September 24, 2013, was received from Lumos Labs. The data set was trimmed to exclude those who indicated on a lifestyle questionnaire that they had a medical condition that prevented getting regular activity and those reporting an age less than 13 or older than 89.99. The final sample included in the analysis consisted of 8752 Lumosity users. The research was completed in accordance with the Helsinki Declaration.

Outcome Measures

Online Flanker Task

Participants freely chose to log onto the Lumosity Web site to play or train on one or more cognitive games (Sternberg et al., 2013). The present analysis focused on the game *Lost in Migration* (http://blog.lumosity.com/the-science-behind-lost-in-migration) because it is a modified Ericksen flanker task (Eriksen & Eriksen, 1974). Before the task, instructions were provided. A first screen was presented with the instructions to "spot the direction of the center bird, do not let the others distract you—some are lost in migration!". A second screen was presented that included instructions to "press keyboard arrows to input the direction of the central bird" and showed icons of the four arrow keys of a standard computer keyboard. The arrow keys were the only potential valid response options, other key presses were inaccurate responses. Pressing the start button on the third screen started the 45-s task. During the task, each screen shows a flock of five birds. The goal was to use the arrow keys on a keyboard to indicate the direction that the central bird was facing as accurately and quickly as possible. Once the game started, a new flock of birds appeared immediately after each response, regardless of accuracy, until 45 s had elapsed at which time that game was over. Each 45-s game was a block. The head of the central bird faced either up, down, left or right, and the direction of the central bird could change with each flock presented. In all presentations, there were four flanking birds, two on each side of the central bird. On half of the presentations in each block, the birds all faced in the same direction (congruent trials), and on the other presentations the central bird faced a direction opposite of that of the other four flanking birds (incongruent trials). Here, we focused on performance accuracy, which often differs between young and old (Spreng, Wojtowicz, & Grady, 2010), during the congruent and incongruent presentations. Reaction time data were not included because the precise timing of visual stimuli presentation and the accuracy of reaction time data can be influenced by differences in software and hardware configurations and internet connections speeds (Birnbaum, 2004). The day on which the game was played was recorded and used in the analysis. Some players completed five blocks on the same day while others took days or months to complete five blocks. Some players completed some or all of their five blocks as part of a "daily workout" in which the types of games played are determined by a proprietary algorithm. Other players made the decision to play the *Lost in Migration* game for some or all of their blocks after navigating to the "free play" part of the website. This variable (i.e., "daily workout" *vs.* "free play") was used in the analysis.

Physical activity and lifestyle questions

Participants were asked two questions about their physical activity: "In a typical week, how many times do you engage in aerobic exercise (e.g., running, cycling, aerobics, swimming, brisk walking, hiking, etc.)?" and "In a typical week, how many times do you engage in resistance exercise (e.g., lifting weights, push-ups, sit-ups, etc.)?" Responses used were never, rarely and 1–7 days per week.

Participants were asked "Do you smoke?" (possible responses were - yes or no)", "How many hours of sleep do you typically get each night?" (less than 4 hr in hour increments up to more than 10 hr), "What is your education level?" (1 = some high school, 2 = high school, 3 = some college, 4 = associate, 5 = bachelors, 6 = masters, 7 = professional, 8 = Ph.D.), and "On average, how many cups of caffeinated coffee or tea do you drink each day?" (0 to ≥5 cups).

Statistical Analysis

Latent transition and class analysis

Participants in the cohort were classified as performing "daily workouts" or "free play" or as completing sessions within a day or between days across the blocks using latent transition analysis (LTA) by M*plus* 7.3 (Muthén & Muthén, 1998–2012). LTA provided Bayesian probability estimates of people being classified into those groups based on their observed status at each block. Model fit was tested using a robust maximum likelihood ratio test. The number of classes was tested by a significant chi-square change (χ^2 Δ) estimated by a bootstrapped likelihood ratio test.

Latent growth modeling

Trajectories of change in percent accuracy were estimated using latent growth modeling (Bollen & Curran, 2006) in M*plus* 7.3 All models were adjusted for between- and within-participant variation in time between blocks using a multilevel random slopes model that uses individually varying time periods of observations within each person to model change. Aerobic activity and age were each centered on their sample means. Other multivariate adjustments were made for between-participant differences by including the following covariates in the growth model: age at block 1, gender, education level, smoking, sleep, Lumosity training status (i.e., "daily workout" or "free play"), completing sessions within a day or between days, and caffeinated coffee or tea consumption. Near complete data were obtained for accuracy of the flanker task (0.002% missing on one block, 0% on the other blocks) and the lifestyle questions, which ranged from 0% missing for aerobic exercise frequency to 0.8% missing for resistance exercise frequency. The MLR estimator uses full-information to impute missing values and is robust to non-normality and up to 25% missing data (Enders & Bandalos, 2001). Robust maximum likelihood parameters and their standard errors were estimated for initial status (i.e., mean at baseline), change (i.e., trajectory of differences across the five blocks), and the variances (i.e., inter-individual and intra-individual differences) of initial status and change. Model fit was evaluated using the chi-square (χ^2) statistic, comparative fit index (CFI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR) (Hu & Bentler, 1999). Values of CFI ≥ 0.90 were judged to be acceptable, while values >0.95 indicated good fit. Values of the RMSEA ≤ 0.06 and ≤ 0.08 indicated close and acceptable fit. Concurrent values ≥ 0.95 for CFI and ≤ 0.08 for SRMR provide optimal protection against type I and type II error rates. A significant interaction was decomposed using standard procedures (Aiken & West, 1991).

RESULTS

Demographics and Descriptive Findings

Demographics and raw cognitive performance data for the sample are presented by age group, aerobic exercise frequency, and resistance exercise frequency in Tables 1, 2, and 3, respectively. The mean (*SD*) number of total flanker trials completed within each of the five blocks were 42.8 (15.7), 45.6 (15.2), 46.8 (16.2), 47.4 (15.9), and 48.1 (16.0) for blocks 1–5, respectively.

Table 1. Demographics of participants and unadjusted cognitive performance data by age group

	13–19	20–29	30–39	40–49	50–59	60–69	70–79	80–89	Total
No. of participants (% sample)	942 (10.8%)	1713 (19.6%)	1052 (12.0%)	1206 (13.8%)	1788 (20.4%)	1493 (17.1%)	479 (5.5%)	79 (0.9%)	8752 (100%)
Proportion female - %	40.0	37.0	47.1	63.7	73.7	75.2	65.3	62.0	58.0
Proportion smoker -%	9.70	18.0	16.3	10.8	7.7	5.7	1.7	0	10.5
Age at signup	17.01 (1.95)	24.46 (2.79)	34.63 (2.88)	45.44 (2.88)	55.14 (2.88)	64.36 (2.82)	73.94 (2.75)	82.99 (2.11)	44.08 (18.18)
Hours of sleep	7.57 (2.17)	7.19 (1.74)	6.91 (1.37)	6.89 (1.33)	6.93 (1.28)	7.05 (1.34)	7.12 (1.53)	6.95 (1.19)	7.08 (1.55)
Aerobic exercise (days/week)	3.25 (2.15)	2.62 (1.94)	2.54 (1.94)	2.65 (1.95)	2.88 (2.02)	2.96 (2.01)	2.87 (1.98)	2.92 (2.00)	2.81 (2.00)
Resistance exercise (days/week)	2.49 (2.17)	2.08 (1.84)	1.73 (1.66)	1.67 (1.69)	1.74 (1.73)	1.72 (1.68)	1.79 (1.89)	1.70 (1.82)	1.88 (1.81)
Education level	2.27 (1.09)	4.37 (1.57)	4.85 (1.65)	4.63 (1.69)	4.58 (1.63)	4.72 (1.64)	4.62 (1.82)	4.75 (2.03)	4.36 (1.76)
Daily drinks of caffeinated coffee or tea	0.76 (1.35)	1.54 (1.91)	2.13 (2.39)	2.42 (2.52)	2.43 (2.38)	2.15 (2.19)	1.96 (1.88)	1.91 (2.48)	1.96 (2.23)
Total attempts in first block of *Lost in Migration*	54.11 (12.84)	53.66 (13.25)	47.67 (14.12)	40.86 (14.02)	37.61 (13.06)	33.19 (11.99)	28.51 (11.47)	25.49 (11.48)	42.82 (15.69)
Congruent unadjusted accuracy in first block of *Lost in Migration* - %	97.65 (6.53)	98.29 (4.87)	97.96 (5.62)	97.47 (7.35)	97.23 (7.51)	97.17 (7.61)	96.24 (10.89)	97.27 (7.34)	97.54 (7.00)
Incongruent unadjusted accuracy in first block of *Lost in Migration* - %	92.36 (10.6)	94.6 (8.70)	95.1 (10.46)	94.56 (11.84)	94.85 (11.81)	94.60 (12.25)	92.74 (15.88)	92.90 (15.40)	94.35 (11.40)

Note. Means are reported unless otherwise specified. Standard deviations are in parentheses except for the "number of participants" variable.

Table 2. Demographics of participants and unadjusted cognitive performance data by typical weekly frequency of aerobic exercise

	Typical aerobic exercise bouts (frequency per week)									
	Never	Rarely	1	2	3	4	5	6	7	Total
Number of participants (% sample)	487 (5.6%)	1442 (16.5%)	874 (10.0%)	1248 (14.3%)	1776 (20.3%)	973 (11.1%)	970 (11.1%)	446 (5.1)	536 (6.1%)	8752 (100%)
Proportion female (%)	62.6	63.4	57.5	55.5	57.9	58.4	55.0	52.8	54.9	58.0
Proportion smoker (%)	17.2	16.4	10.8	8.4	9.7	8.5	7.8	4.9	9.3	10.5
Age at signup	46.20 (17.98)	43.10 (17.62)	42.09 (17.28)	43.77 (17.81)	45.01 (18.11)	45.09 (18.26)	44.17 (18.93)	45.18 (19.22)	42.81 (19.47)	44.08 (18.18)
Hours of sleep	7.11 (2.10)	6.99 (1.95)	7.09 (1.65)	7.11 (1.53)	7.07 (1.27)	7.02 (1.07)	7.12 (1.29)	7.14 (1.49)	7.16 (1.61)	7.08 (1.55)
Education level	4.19 (1.78)	4.16 (1.72)	4.46 (1.71)	4.43 (1.73)	4.43 (1.72)	4.48 (1.79)	4.42 (1.77)	4.38 (1.82)	4.07 (1.88)	4.36 (1.76)
Daily caffeinated drinks	2.38 (2.67)	2.11 (2.43)	1.92 (2.20)	1.95 (2.16)	1.87 (2.08)	2.03 (2.21)	1.84 (2.10)	1.63 (1.83)	1.94 (2.39)	1.96 (2.23)
Total attempts in first block of *Lost in Migration*	39.79 (16.17)	41.93 (15.46)	43.28 (16.37)	43.23 (15.53)	42.65 (15.58)	42.59 (15.63)	43.70 (14.98)	44.63 (16.24)	44.19 (15.91)	42.82 (15.69)
Congruent unadjusted accuracy in first block of *Lost in Migration* - %	97.52 (6.92)	97.37 (7.30)	97.41 (8.23)	97.54 (7.16)	97.54 (6.91)	97.78 (5.98)	97.64 (6.84)	97.87 (6.06)	97.33 (6.81)	97.54 (8.74)
Incongruent unadjusted accuracy in first block of *Lost in Migration* - %	93.13 (14.24)	94.23 (11.70)	94.04 (12.57)	94.71 (11.02)	94.46 (11.32)	94.57 (10.66)	94.78 (10.23)	93.77 (11.87)	94.37 (9.56)	94.35 (11.40)

Note. Means are reported unless otherwise specified. Standard deviations are in parentheses except for the "number of participants" variable.

Latent Transition and Class Analysis

The best fitting models indicated two classes of cases for sessions [3347 participants (38%) completed blocks within the same day and 5405 participants (62%) completed blocks on different days; χ^2 Δ (6) = 8968.5; $p < .001$] and for Lumosity training status [6111 participants (70%) played the game as part of a "daily workout" and 2641 participants (30%) played as part of free play; χ2 Δ (6) = 55729; $p < .001$]. Classification probabilities were 95% for sessions and 99% for training status. The mean (± *SD*) time between sign-up to play and block 1 of the *Lost in Migration* game was 8.2 months (±3.7 months). Thirty-nine percent to 43% of the five blocks occurred within 24 hr. Between blocks 2 to 5, the mean (± *SD*) inter-day time between blocks ranged from 14 to 16 days (±27 to 30) days. The mean (± *SD*) intra-day time between blocks ranged from 3.8 to 4.0 hr (±7.6 to 7.9 hr). Sixty-seven percent to 71% of the blocks occurred during Lumosity training.

Participants who subsequently were more likely to complete blocks on different days were 2% more accurate at block 1 [95% confidence interval (CI), 1.8% to 2.30%; z = 15.5; $p < .001$], but they had similar linear (p = .649) and quadratic (p = .856) change compared to participants who were more likely to complete blocks during the same day. Similarly, participants who were more likely to have performed the blocks as part of a "daily workout" were 1.8% more accurate at block 1 (95% CI, 1.54% to 2.14%; z = 12.05; $p < .001$), but they had similar linear (p = .660) and quadratic (p = .972) change compared to those who were not enrolled.

Growth Models

Incongruent presentations across five blocks

Figure 1 shows unadjusted accuracy during incongruent presentations during blocks 1 through 5. Accuracy increased from 94.4% at block 1 to 95.4% at block 2 and was stable thereafter (ICC-2, 5 = .70, 95% CI, .68–.72). Growth modeling indicated linear increase [B = 0.600%, 95% CI, 0.42 to 0.78; z = 6.53; $p < .001$] from the estimated initial score of 94.6% (95% CI, 94.4 to 94.8) followed by a quadratic deceleration [B = –0.109%; 95% CI, –0.015 to –0.002; *SE* = 0.021; z = 5.32; $p < .001$], resulting in a net 0.491% increase in accuracy on blocks 2–5. Variance was 14%, (*SE* = 4%, p = .001) for the linear slope and 0.5% (*SE* = 0.19%; p = .005) for the quadratic slope. Model fit was good (χ^2 (6) = 15.5; p = .02; CFI = 0.992; RMSEA = .013 (.005–.022), SRMR = .044). After adjustment for variation in time between blocks, aerobic activity was unrelated to accuracy on block 1 (p = .807), but it was positively related to linear increase in accuracy (B = 0.713%; 95% CI, 0.256 to 1.170) and inversely related to the quadratic deceleration of accuracy gains (B = – 0.767%; 95% CI, –1.251 to –0.283).

Figure 1 shows predicted accuracy during incongruent presentations during blocks 1 through 5, after adjustment for time between blocks, covariates, sessions, and training status.

Table 3. Demographics of participants and unadjusted cognitive performance data by typical weekly frequency of resistance exercise

	Typical resistance exercise bouts (frequency per week)									
	Never	Rarely	1	2	3	4	5	6	7	Total
Number of participants (% sample)	1347 (15.5%)	2148 (24.8%)	1009 (11.6%)	1320 (15.2%)	1453 (16.8%)	552 (6.4%)	441 (5.1%)	185 (2.1%)	211 (2.4%)	8666 (100%)
Proportion female (%)	73.4	62.3	62.1	59.39	50.4	40.0	38.0	37.8	38.4	57.8
Proportion smoker (%)	13.1	11.9	10.1	9.2	8.9	11.6	8.2	6.5	7.6	10.5
Age at signup	47.49 (17.79)	44.20 (17.78)	43.52 (17.28)	45.63 (17.82)	44.16 (18.22)	39.81 (18.15)	38.71 (18.62)	39.93 (19.91)	36.53 (20.36)	44.00 (18.17)
Hours of sleep	7.11 (1.87)	7.03 (1.58)	7.09 (1.52)	7.06 (1.39)	7.10 (1.26)	6.97 (1.26)	7.04 (1.24)	7.27 (1.73)	7.27 (2.19)	7.07 (1.54)
Education level	4.36 (1.79)	4.31 (1.72)	4.46 (1.78)	4.55 (1.69)	4.40 (1.73)	4.33 (1.80)	4.04 (1.77)	4.09 (1.81)	3.75 (1.96)	4.36 (1.76)
Daily caffeinated drinks	2.22 (2.50)	2.05 (2.30)	1.98 (2.20)	1.90 (2.00)	1.84 (2.07)	1.71 (2.06)	1.67 (1.93)	1.77 (2.23)	1.83 (2.65)	1.96 (2.22)
Total attempts in first block of *Lost in Migration*	39.73 (15.41)	42.21 (15.42)	42.88 (15.20)	42.20 (15.82)	43.79 (15.24)	46.36 (15.80)	46.57 (15.98)	47.58 (17.56)	47.27 (16.42)	42.89 (15.68)
Congruent unadjusted accuracy in first block of *Lost in Migration* - %	97.17 (8.02)	97.50 (7.18)	97.32 (7.69)	97.55 (7.48)	98.10 (4.56)	97.63 (6.71)	97.86 (5.12)	96.95 (8.53)	97.76 (5.05)	97.56 (6.94)
Incongruent unadjusted accuracy in first block of *Lost in Migration* - %	93.44 (15.12)	94.43 (11.34)	94.46 (11.45)	94.70 (10.75)	94.61 (11.14)	94.52 (9.94)	95.08 (8.06)	93.90 (9.88)	93.93 (9.95)	94.36 (8.68)

Note. Means are reported unless otherwise specified. Standard deviations are in parentheses except for the "number of participants" variable.

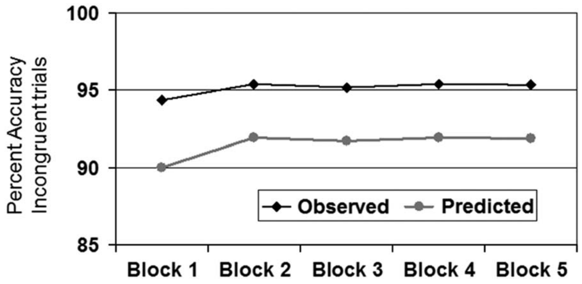

Fig. 1. Observed and predicted accuracy during the incongruent flanker trials presented within five 45-s blocks. Mean ±95% confidence interval. The 95% CIs are too small to be observed in the figure but are ~0.20% for the observed and ~0.10% for the predicted data.

Aerobic physical activity remained unrelated to accuracy during block 1 ($p = .692$) (Table 4). Accuracy on block 1 was higher in older players, those with more education, in women, those who drank more coffee or tea, and those who were more likely to have played the game as part of a "daily workout" or complete blocks on different days. Aerobic activity was positively related to linear increase in accuracy (B = 0.577%; 95% CI, 0.112 to 1.25) and inversely related to the quadratic deceleration of accuracy gains (B = −0.619%; 95% CI, −1.117 to −0.121). For each day of aerobic physical activity above the mean of 2.8 days, there was approximately six-tenths of a percent linear increase in accuracy and six-tenths of a percent less deceleration in accuracy. Thus, people who reported above-average aerobic physical activity attained and maintained a higher accuracy during incongruent blocks 2–5 compared to people who reported below-average activity. In addition, the interaction of aerobic physical activity with age was inversely related to the linear increase in accuracy (B = –0.031%; 95% CI, –0.05 to –0.01; $p = .005$) and positively related to the quadratic deceleration of increased accuracy (B = 0.03%; 95% CI, 0.01 to 0.05; $p = .01$). Figures 2 and 3 show that physically active participants younger than age 45 had a larger linear increase and a smaller quadratic deceleration compared to other participants.

Resistance activity was unrelated to accuracy at block 1 (B = 0.042; $SE = 0.033$; $p = .205$) or to linear (B = 0.239; $SE = 0.261$; $p = .361$) and quadratic (B = –0.143; $SE = 0.305$; $p = .638$) change.

Congruent presentations across five blocks

After adjustment for variation in time between blocks, aerobic activity was unrelated to accuracy on block 1 (B = 0.010%; $SE = 0.023$; $p = .653$), but it was positively related to linear increase in accuracy (B = 0.427%; 95% CI, 0.084 to 0.770) and inversely related to the quadratic deceleration of accuracy gains (B = −0.449% CI, –0.817 to –0.081). Thus, people who reported above-average aerobic physical activity attained and maintained a higher accuracy during congruent blocks 2–5 compared to people who reported below-average activity.

Table 4. Fully adjusted growth model for accuracy during incongruent trials within the first block of the flanker task in relation to aerobic exercise

Block 1 on	Beta weight	Standard error	*z*-statistic	*p* Value (two-tail)
Aerobic activity	0.012	0.030	0.396	0.692
Age	0.026	0.005	5.679	<.001
Education	0.363	0.038	9.527	<.001
Gender	0.599	0.125	4.800	<.001
Smoking	0.264	0.177	1.495	.135
Sleep	–0.384	0.334	–1.149	.251
Coffee or tea	0.298	0.079	3.788	<.001
Sessions	1.437	0.142	10.147	<.001
Training	0.845	0.169	5.014	<.001
Linear growth on	**Beta weight**	**Standard error**	***z*-statistic**	***p* Value (two-tail)**
Aerobic activity	0.577	0.237	2.433	.015
Age	–0.076	0.033	–2.304	.021
Education	–0.285	0.273	–1.045	.296
Gender	–0.837	1.022	–0.819	.413
Smoking	–1.193	1.360	–0.877	.380
Sleep	–3.964	2.248	–1.763	.078
Coffee or tea	–0.698	0.597	–1.169	.242
Sessions	1.138	1.128	1.008	.313
Training	0.061	1.377	0.044	.965
Quadratic growth on	**Beta weight**	**Standard error**	***z*-statistic**	***p* Value (two-tail)**
Aerobic activity	–0.619	0.254	–2.437	.015
Age	0.015	0.036	0.442	.673
Education	0.509	0.297	1.715	.086
Gender	0.596	1.079	0.553	.580
Smoking	1.400	1.434	0.976	.329
Sleep	4.540	2.229	2.036	.042
Coffee or tea	0.790	0.643	1.229	.219
Sessions	–0.509	1.235	–0.412	.680
Training	–0.550	1.576	–0.349	.727

After adjustment for varying time between blocks, covariates, sessions, and training status Table 4), aerobic physical activity was unrelated to congruent accuracy during block 1 (B = 0.017; *SE* = 0.022; *p* = .445), linear change (B = 0.289; *SE* = 0.183; *p* = .113), and quadratic change (B = –0.315; *SE* = 0.187; *p* = .092). Accuracy on block 1 was higher in players with more education, in women, those who drank more coffee or tea, and those who were more likely to have been those to have played the game as part of a "daily workout" or complete blocks on different days.

Resistance activity was unrelated to accuracy during congruent presentations during block 1 (B = –0.022; *SE* = 0.034; *p* = .523), linear change (B = 0.252; *SE* = 0.452; *p* = .578), and quadratic change (B = –0.142; *SE* = 0.688; *p* = .837).

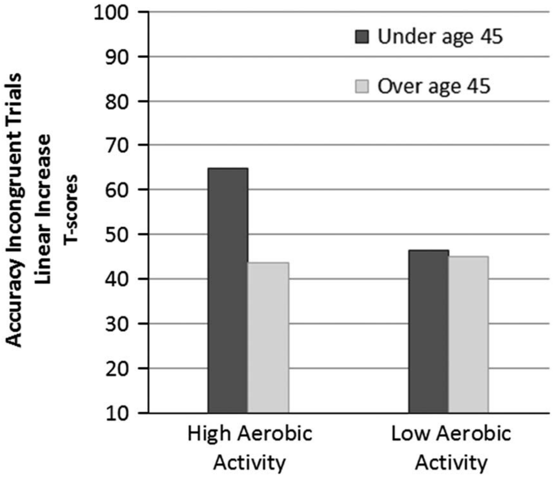

Fig. 2. Aerobic activity-by-age linear effect on predicted accuracy during incongruent trials.

DISCUSSION

Results for Change across Blocks 1 to 5

The primary finding from the present investigation was that for the more cognitively demanding, incongruent flanker task items, the frequency of aerobic exercise was positively related to increased accuracy that occurred between block 1 and 2, and inversely related to deceleration of accuracy gains across blocks 2 to 5. Thus, people who reported above-average aerobic physical activity attained and maintained a higher accuracy during incongruent blocks 2–5 compared to people who reported below-average activity. More particularly, those under age 45 who reported higher than average frequency of aerobic activity showed the largest increase in incongruent accuracy from block 1 to 2 and also less deceleration in accuracy from blocks 2 to 5 compared to those over age 45 who reported below average aerobic activity.

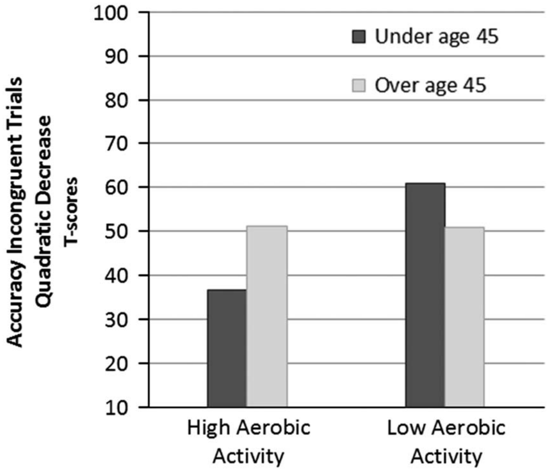

Fig. 3. Aerobic activity-by-age quadratic effect on predicted accuracy during incongruent trials.

We have been unable to find prior studies documenting changes in flanker performance accuracy analyzed across multiple blocks of ~46 trials, either within a session on a single day or across days. Some studies have not specified the number of trials or blocks (McAuley, Mullen, et al., 2011), others have analyzed a single block of 40 to 160 flanker trials (Gothe et al., 2014) and some have averaged multiple blocks of fewer trials per block (e.g., 17–20 trials) (Colcombe et al., 2004). Thus, it is not possible to directly compare the present findings to similar published studies. Performance on the flanker test can improve with practice, especially in incongruent presentations for which there is less potential for practice effects to be attenuated by a ceiling effect. Test–retest changes in mean-level performance have been quantified using nearly 1600 effects from published neuropsychological test results, and executive function and attention tasks were found to be reduced by ~.01 SD across a 1-year time frame (Calamia, Markon, & Tranel, 2012). In this meta-analysis, separate effects were not provided for flanker tasks and no quantitative review of shorter-term changes in flanker performance, such as within a single day or across a week or a month, has been published. In the one study examining flanker accuracy, practice effects were found to be largest during the first six trials compared to subsequent trials (Cohen-Kdoshay & Meiran, 2009). The potential moderating effect of age was not considered.

There appears to be inadequate prior experimental evidence to draw a strong conclusion as to whether the magnitude of flanker performance is moderated by age. The larger increase in accuracy between block 1 and 2 and the attenuated deceleration of accuracy gains between blocks 2 and 5 for aerobically active participants younger than age 45 found here is generally consistent with prior research on age and practice effects. In a sample of 1616 adults ranging from 18 to over 80 years of age, the magnitude of practice effects were negatively correlated with age across a range of cognitive tasks, including memory (Salthouse, 2010). Although tasks focused on cognitive control, such as the Stroop or flanker, were not examined, the group-level correlation between mean age and the estimated practice effect across 2.5 years for memory was $-.86$ (Salthouse, 2010). The findings in the literature are not unanimous, for example, a larger practice effect, defined by the time it took to complete the Stroop task, was reported in 638 participants ≥ 80 years of age compared to 1174 participants ≤ 71 years of age in the PROSPER trial (Houx et al., 2002).

Aerobic fitness has not been linked previously to learning across blocks of a flanker task but has been considered in relation to the initial trials of at least two cognitive tasks. Aerobic fitness in 30 adolescents was significantly and positively associated with learning during the first six trials of a virtual Morris Water Maze task which measures aspects of visuospatial memory (Herting & Nagel, 2012). In a separate study of eight adults under age 46, both aerobic fitness at the end of 3-months of exercise training and changes in aerobic fitness were significantly and positively associated with improvements in immediate recall of the first 20 words presented in a modified Rey Auditory Verbal Learning Test (Pereira et al., 2007).

Although the flanker task has been described as emphasizing cognitive control, performance on the version of the task used here also required adequate motivation, working memory and sustained attention (Botvinick & Braver, 2015). Physical activity may have been associated with any or all of these processes thought to underlie flanker task performance. Working memory historically is thought to be a trait (Baddeley, 2003) with a strong genetic component (Friedman et al., 2008). Contemporary findings suggest that working memory can be improved to a degree and suggest that the underlying neural circuity has some plasticity in response to interventions such as intense cognitive training or exercise training (Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Mahncke et al., 2006; McNab et al., 2009; Nagamatsu et al., 2013; Padilla, Pérez, & Andrés, 2014; Sprenger et al., 2013; Volkers & Scherder, 2014) or their combination (Smith et al., 2013).

The mechanisms by which physical activity or inactivity could alter working memory are unclear, but are being investigated. Research with older adults, for instance, found that higher aerobic fitness levels attenuated age-associated reductions in N-acetylaspartate, a metabolite found in neuronal cell bodies that is decreased in Alzheimer's disease, and that higher N-acetylaspartate concentrations mediated the association between aerobic fitness and working memory (Erickson et al., 2012). Whether this observation generalizes to practice effects is unknown.

Some evidence, although not all (Pontifex, Hillman, & Polich, 2009), suggests that exercise training can influence brain regions known to be involved in attention (Colcombe & Kramer, 2003; Pérez, Padilla, Parmentier, & Andrés, 2014). The present findings might be explained by improvements in attention processes needed to select or inhibit a correct response, including a specific motor response. The basal ganglia are thought to be involved in the selection of a needed motor program and the active inhibition of an unneeded one (Boraud, Bezard, Bioulac, & Gross, 2002; Mink, 1996). Also, studies of rodents and patients with Parkinson's disease show that neuroplasticity in basal ganglia results from exercise-induced alterations in dopamine and glutamate (Petzinger et al., 2010). Compared to less aerobically fit older adults, more highly fit older adults showed different activation of the anterior cingulate cortex and better flanker performance (Colcombe et al., 2004). In contrast, anterior cingulate cortex activation was not altered after resistance training in older adult despite improvement in flanker performance (Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012), consistent with the observation here that resistance training was unrelated to flanker performance.

Practice of attentional tasks alters brain activation responses. For example, decreases in anterior cingulate cortex activity and increases in dorsolateral prefrontal cortex activity during the Stroop were reduced in later practice trials compared to early practice trials (Erickson et al., 2004). The neural basis for physical activity or fitness influences on practice effects in tasks involving cognitive control rarely has been investigated. Compared to less fit children and during a flanker task, higher fit children showed greater activation of the anterior cingulate cortex but only in the early task block. Early was defined as the first 195 s (Chaddock et al., 2012). Whether those findings extend to adults is unknown.

The literature shows that the potential influence of aerobic fitness and physical activity on practice effects has frequently been ignored. The present findings underscore the potential usefulness of systematically including an analysis of practice effects in investigations of physical activity and cognitive function. Such data may be useful in predicting important cognitive health outcomes (Duff et al., 2010) and also may offer an alternative hypothesis when exercise appears to have effects on cognitive performance at one age but not another.

Block 1 Results

A second finding was that accuracy at block 1, for both the congruent and incongruent flankers task, was unrelated to the frequency of either aerobic or resistance exercise. Only a few studies have examined the relationship between a single block of flanker data and physical activity or fitness. One study that analyzed a single block of 64 flanker trials found that lower aerobic fitness was associated with greater variability in flanker reaction time, and this effect increased with age but no information was reported about flanker accuracy (Bauermeister & Bunce, 2014). A study of 179 older adults reported a weak correlation ($r = .112$) between incongruent flanker performance and estimated maximal oxygen consumption and the flankers appeared to have been presented in a single block (Verstynen et al., 2012).

Although it is unknown if any caffeine was consumed before the flanker tasks were performed, it was perhaps not surprising that block 1 performance was better among participants who reported consuming more caffeinated coffee or tea. Caffeine acts on dopamine rich brain areas involved in the executive control of visual attention (Lumme, Aalto, Ilonen, Någren, & Hietala, 2007) and can have dose-response effects on flanker performance (Brunyé, Mahoney, Lieberman, & Taylor, 2010). It also was not surprising that incongruent accuracy at block 1 was better among participants with a higher level of education because attention and motivation is crucially important for many types of learning and self-regulation that contributes to educational success (Posner & Rothbart, 2005). Less certain is why older adults, women, those likely to complete blocks on different days and those likely to be performing the *Lost in Migration* game as part of a "daily workout" were better performers at block 1. Those electing to play cognitive games as part of a "daily workout" may have done so because of worry about cognitive decline or they had stronger perceptions of wanting to maintain cognitive health and consequently been more strongly motivated from the outset to perform well. Relatively little is known about why some older adults are motivated to engage in cognitive training using online games (Herman, de Kort, & Ijsselsteijn, 2009).

Demographic and Descriptive Results

The proportion of the sample reporting never or rarely engaging in physical activity (22.1%) was lower than U.S. population estimates for adults (26.1%) (Carroll et al., 2014) and higher than high school students (15.2%) (Kann et al., 2014). A higher percentage of the sample reported engaging in two or more weekly bouts of strengthening physical activity compared to estimates for the U.S. population (48% *vs.* 29.3%) (Centers for Disease Control, 2013). The number of hours slept and number of daily drinks of caffeinated coffee or tea were generally consistent with U.S. population estimates (Frary, Johnson, & Wang, 2005; Kripke, Garfinkel, Wingard, Klauber, & Marler, 2002). The proportion of the sample that smoked was lower than the 2005–2012 estimated prevalence for adults in the U.S. (10.5% *vs.* 18.1%) (Agaku, King, & Dube, 2014). The lower accuracy in the more cognitively challenging incongruent flankers compared to the congruent flankers also was consistent with expectations based on prior research (Sanders & Lamers, 2002).

LIMITATIONS AND CONCLUSIONS

The present investigation had several limitations. Participants were not randomly selected from a well-defined population but did have access to the internet and chose to play the *Lost-In-Migration* game at least five times. Thus, the generalizability of the findings to the population at large, which includes people without internet access and those with no interest in online game playing, is uncertain.

The self-reported demographic and health data obtained were not verified and are potentially inaccurate. A systematic and quantitative review of studies comparing self-reported to objectively measured body weight, for example, showed that people have a tendency to report their weight as lower than their actual body weight (Gorber, Tremblay, Moher, & Gorber, 2007). Whether this is true for the demographic and health data obtained here is uncertain. Notwithstanding, the measurement limitations of self-reported variables, there is little reason to think that such measurement errors would systematically bias the relations seen here with flanker performance.

Although we controlled for several potential confounding variables, no adjustments were made for others such as socioeconomic status or alcohol use. These variables are associated with both physical activity and cognitive performance and may have contributed to some of the findings observed here. For example, the Whitehall II study found that alcohol intake was associated with less physical activity and a reduced risk of poor cognitive function (Britton, Singh-Manoux, & Marmot, 2004; Steinmo, Hagger-Johnson, & Shahab, 2014).

The single-item self-reported physical activity frequency questions that were used lacked information about duration and intensity. Thus, the present results are limited to self-reported exercise frequency and provide no insight into relationships that exercise duration, intensity, or total volume of exposure may have on trajectories of change in flanker performance. Single-item scales reduce participant burden and allow for data collection from large numbers of individuals who otherwise may be unwilling to provide physical activity information. Single item physical activity frequency questions similar to the questions used in this study were found to have strong repeatability and moderately strong associations with aerobic fitness or markers of cardiometabolic health (Churilla, Magyari, Ford, Fitzhugh, & Johnson, 2012; Kohl, Blair, Paffenbarger, Macera, & Kronenfeld, 1988; Loprinzi, Loenneke, & Abe, 2015; Milton, Bull, & Bauman, 2010).

The conditions under which the online game was played were unsupervised and uncontrolled (e.g., the size of the screen, lighting conditions, distractions in the environment), factors which may have altered or weakened effects that might have been observed if the data were obtained under laboratory conditions. No comparison was made between the incongruent trials of the flanker task that followed congruent trials and those that followed incongruent trials or *visa-versa*. Consequently no insight was obtained about potential aerobic or resistance exercise effects on phenomena such as feature repetition bias (Mayr, Awh, & Laurey, 2003) or congruency switch costs (Schmidt & De Houwer, 2011). Also, the analysis did not account for potential confounders such as prior experiences with online game playing or potential age-related variations in regular video game participation, engagement and interest (Festl, Scharkow, & Quandt, 2013; Kim, Park, & Baek, 2009).

Bearing in mind the limitations mentioned, this investigation suggests that (i) accuracy during the first block of an online flanker task, for both the congruent and incongruent flankers, was unrelated to the frequency of either self-reported aerobic or resistance exercise; and (ii) age moderates the association between, self-reported aerobic, but not resistance, exercise and changes in cognitive control that occur during the initial five blocks of an online flanker task. The present findings underscore the potential usefulness of systematically including an analysis of practice effects in investigations of physical activity and cognitive function.

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