Brain and Language 198 (2019) 104681

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Aerobic fitness relates to differential attentional but not language-related cognitive processes

Madison C. Chandler[a], Amanda L. McGowan[a], Brennan R. Payne[b], Amanda Hampton Wray[c], Matthew B. Pontifex[a,*]

[a] Department of Kinesiology, Michigan State University, 308 W. Circle Drive, East Lansing, MI 48824, United States
[b] Department of Psychology, University of Utah, 380 S 1530 E Beh S 502, Salt Lake City, UT 84112, United States
[c] Department of Communication Science & Disorders, University of Pittsburgh, 6035 Forbes Tower, Pittsburgh, PA 15260, United States

ARTICLE INFO

Keywords:
Aerobic Fitness
Reading
ERPs
N400
P3b
LPC

ABSTRACT

Compelling evidence supports an association between the attribute of aerobic fitness and achievement scores on standardized tests of reading. However, such standardized assessments provide only a broad valuation of a complex network of language related sub-processes that contribute to reading and are heavily confounded by other attention-related processes. The present investigation sought to clarify the nature of the association between aerobic fitness and language processing in a sample of college-aged adults. Participants were bifurcated based on aerobic fitness level and on a separate day were asked to complete a lexical decision task while neuroelectric activity was recorded. Analysis of word-level language-related ERP components revealed no fitness differences. However, lower aerobically-fit individuals elicited smaller amplitude for attention-related ERP components relative to the higher aerobically-fit group. These data provide initial evidence to suggest that fitness-related differences in reading achievement may result from attentional processes rather than acting upon specific language-related processes.

1. Introduction

The past several decades have seen a growing interest in health neuroscience research given an increased understanding that physical activity engagement not only provides physiological benefits, such as maintaining cardiac health and reducing the risk of chronic disease, but also is important for brain health (Physical Activity Guidelines Advisory Committee, 2018; ParticipACTION, 2018). In particular, the health-related attribute of aerobic fitness — which describes the ability to sustain aerobic physical activity — has garnered a great deal of interest given that lower aerobic fitness has been associated with poorer integrity of high level cognitive operations and neural networks involving attention, memory, and cognitive control (Hillman, Erickson, & Kramer, 2008; Pontifex et al., 2014, 2011; Voss et al., 2011). Indeed, lower levels of aerobic fitness and reduced habitual physical activity levels have also been associated with differences in academic performance not only in childhood but also through adolescence and into young adulthood, such that lower-fit/active individuals perform worse on standardized achievement tests and have lower grade point averages than their more-fit/active peers (Coe, Pivarnik, Womack, Reeves, & Malina, 2012; Coe, Pivarnik, Womak, Reeves, & Malina, 2006; Kwak et al., 2009; Ruiz et al., 2010; Ruiz-Ariza, Grao-Cruces, de Loureiro, & Martínez-López, 2017; Vasold, Deere, & Pivarnik, 2019; Welk, Jackson, Haskell, Meredith, & Cooper, 2010). Interestingly, these differences in performance appear particularly prominent for academic domains associated with reading (Castelli, Hillman, Buck, & Erwin, 2007; Chu, Chen, Pontifex, Sun, & Chang, 2016; Esteban-Cornejo et al., 2014; Fedewa & Ahn, 2011; Hillman et al., 2008; Janak et al., 2014; Wittberg, Northrup, & Cottrell, 2012). However, given the nature of these standardized tests of reading achievement, it remains unclear to what extent such differences are the result of fitness modulating aspects of language processing or rather occur as a byproduct of differences in attention. The purpose of this investigation was therefore to determine the extent to which individuals at the extremes of the aerobic fitness continuum differ on neural indices of language processing and attention.

According to a theoretical model known as the Bimodal Interactive Activation Model (BIAM), reading is thought to be a complex behavior composed of several distinct yet parallel stages of language processing encompassing orthographic decoding (recognizing letters or visual stimuli), phonological decoding ("sounding out" these letters), and

* Corresponding author at: Department of Kinesiology, 126E IM Sports Circle, Michigan State University, East Lansing, MI 48842-1049, United States.
E-mail addresses: chand138@msu.edu (M.C. Chandler), mcgowa78@msu.edu (A.L. McGowan), brennan.payne@utah.edu (B.R. Payne), hamptonwray@pitt.edu (A. Hampton Wray), pontifex@msu.edu (M.B. Pontifex).

https://doi.org/10.1016/j.bandl.2019.104681
Received 10 May 2019; Received in revised form 7 August 2019; Accepted 22 August 2019
Available online 09 September 2019
0093-934X/

semantic processing (determining the meaning, if any, of the string of letters) (Grainger & Holcomb, 2009). Thus, individuals performing similarly on aggregate reading achievement measures may exhibit a high degree of variability across these specific sub-processes (Woollams, Lambon Ralph, David, Plaut, & Patterson, 2007). The assessment of event-related brain potentials (ERPs), however, provides the temporal precision to index these neural processes, with the sub-components of language processing (orthographic, phonological, and semantic processing) mapping onto distinct ERP components: the NP150, the N250, and the N400, respectively (Chauncey, Holcomb, & Grainger, 2008; Eddy, Grainger, Holcomb, Mitra, & Gabrieli, 2014; Grainger & Holcomb, 2009; Laszlo & Federmeier, 2011).

The N400 — a negative-going deflection with a centroparietal maximum that peaks between 300 and 500 ms following the presentation of a stimulus — is one of the most studied language-related ERP components given that it is believed to reflect the access of meaning-related information from long-term memory (Kutas & Federmeier, 2011; Laszlo & Federmeier, 2014; Lau, Phillips, & Poeppel, 2008; Stites & Laszlo, 2017). Of particular interest is the amplitude of the N400 ERP component, which has been observed to modulate as a function of vocabulary size and reading ability and exhibits a strong correlation with behavioral measures of reading (Coch & Holcomb, 2003; Henderson, Baseler, Clarke, Watson, & Snowling, 2011; Khalifian, Stites, & Laszlo, 2016; Stites & Laszlo, 2017). For example, Coch and Holcomb (2003) found that lower-ability beginning readers exhibited a smaller N400 in response to words than did higher-ability readers, and evidence suggests that language proficiency is associated with differences in N400 amplitude even within young adults, such that less-skilled adult comprehenders evidence a smaller N400 effect in response to semantic stimuli than do their more-skilled peers (Coch & Holcomb, 2003; Landi & Perfetti, 2007; Weber-Fox, Davis, & Cuadrado, 2003). Two other reading-related ERP components — the N/P150 and the N250 — peak between 150 and 350 ms following the presentation of a stimulus and are associated with the orthographic and phonological processing of words, respectively (Barber & Kutas, 2007; Chauncey et al., 2008; Grainger & Holcomb, 2009; Holcomb & Grainger, 2006). Given the critical importance of these processes for supporting language ability, impairments in the ability to recognize word-like visual stimuli (the NP150), to break words down into smaller sound-units (the N250), or to extract meaning from words (the N400) can result in substantial downstream deficits impacting upon scholastic performance (Araújo, Bramão, Faísca, Petersson, & Reis, 2012; Lachmann, Berti, Kujala, & Schröger, 2005; Laszlo & Sacchi, 2015; Sacchi & Laszlo, 2016).

At present, however, despite the critical importance of understanding the nature of the relationship between aerobic fitness and language-related sub-processes; relatively little research has investigated this area and the research that does exist is not only conflicted in its findings and populations assessed but has also adopted an experimental approach that may have allowed modulations in other cognitive processes to confound their findings. In an initial underpowered investigation in this area, Magnié et al. (2000) did not observe any difference in N400 amplitude elicited in response to a sentence processing task in a sample of 20 college-aged young adults bifurcated based upon aerobic fitness. In contrast however, when utilizing a similar sentence processing task in a sample of 46 preadolescent children bifurcated based upon aerobic fitness, Scudder et al. (2014), observed smaller N400 amplitude and longer N400 latency — suggesting slower and less efficient semantic processing — for the lower aerobic fitness group relative to the higher aerobic fitness group. Although language-related ERP components (i.e., NP150, N250, and N400) are popularly elicited through sentence processing tasks such as used by Magnié et al. (2000) and Scudder et al. (2014), a growing body of literature has demonstrated the functional utility of lexical decision tasks (also framed as word recognition tasks). In these tasks, individuals attend to a series of unconnected text stimuli and are instructed to respond based on a set of specific instructions. For instance, a popular variant of this task asks individuals to read each stimulus independently with stimuli comprised of words, pseudowords, acronyms, and illegal strings and to only respond if the stimuli constitutes a name (Khalifian et al., 2016; Laszlo & Federmeier, 2007b, 2007a, 2011, 2014; Laszlo, Stites, & Federmeier, 2012). The unconnected nature of this task – each stimulus being presented in isolation – allows for the examination of specific word-level attributes (e.g., orthographic, phonological, and lexical-semantic features) free of the potential confounds associated with attention, context, and prediction that can occur in sentence-processing tasks which themselves have been observed to modulate N400 amplitude (Curran, Tucker, Kutas, & Posner, 1993; Kemp, Eddins, Shrivastav, & Hampton Wray, 2019; Lau, Holcomb, & Kuperberg, 2012; Payne & Federmeier, 2018). Indeed, the sentence processing task utilized by Scudder et al. (2014) may have enabled higher aerobically fit individuals to utilize context and prediction strategies which may have induced modulations in N400 amplitude independent of actual differences in lexical semantic processing (Curran et al., 1993; Lau et al., 2012).

Interestingly, consistent with this view, Scudder et al. (2014) also observed that individuals in the lower aerobic fitness group exhibited smaller P600 amplitude relative to their higher-fit counterparts. The P600 is typically elicited by violations of syntax or difficult syntactic structures, when it is necessary to allocate greater attentional resources and update contextual representations within working memory; as such, it has been generally clustered amongst a family of positive going potentials — the P3b and Late Positive Component (LPC) — with posterior topographic maxima which provide similar indices of attentional processing (Coulson, King, & Kutas, 1998; Leckey & Federmeier, 2019; Scudder et al., 2014). Specifically, the P3b is a positive-going deflection peaking 300–700 ms following the presentation of a stimulus which provides an index of the allocation of attentional resources, with greater P3 amplitude corresponding to increased suppression of extraneous neural activity in support of context updating (Polich, 2007). Similarly, the LPC occurs 600–900 ms following the presentation of a stimulus during the period following the N400 and is thought to reflect the allocation of attentional resources in support of determining the lexical meaningfulness of the letter array (Laszlo et al., 2012). The finding by Scudder et al. (2014) that lower aerobically fit individuals exhibited smaller P600 amplitude relative to their higher-fit counterparts would thus appear consistent with the extant fitness and attention literature, which has observed smaller P3b amplitude in response to simple stimulus-discrimination oddball paradigms for lower aerobically fit individuals relative to higher aerobically fit individuals across the lifespan (Hillman, Castelli, & Buck, 2005; Pontifex, Hillman, & Polich, 2009). However, it is important to note that there remains debate as to the functional significance of the P600 ERP component and the extent to which the P3b, LPC, and the P600 should be viewed as conceptually similar (Frisch, Kotz, von Cramon, & Friederici, 2003; Sassenhagen, Schlesewsky, & Bornkessel-Schlesewsky, 2014).

Taken together, further investigation is necessary to better elucidate the relationship between aerobic fitness and language processing utilizing a lexical decision task to reduce potential confounds and enable the examination of potential fitness related differences in orthographic decoding (the NP150), phonological decoding (the N250), and semantic processing (the N400). Further, lexical decision tasks conceptually align with the popular oddball-task — as the target stimulus (i.e., when the letter stimuli constitute a name) occurs relatively infrequently amongst an array of words, pseudowords, acronyms, and illegal strings — enabling this task to also characterize attention-related cognitive processes by assessing the P3b ERP component elicited by the target stimulus as well as the LPC component elicited by non-target stimuli. This initial investigation utilized a sample of college-aged young adults given previous findings across the lifespan demonstrating aerobic fitness related differences in attention-related cognitive processes— as assessed by the P3b elicited in response to the oddball task (Hillman et al., 2005; Hillman, Kamijo, & Pontifex, 2012; Pontifex et al., 2009), and to reduce potential differences in language processing associated with language proficiency. Accordingly, in a well-powered sample, the present investigation sought to characterize the extent to which individuals at the extremes of the aerobic fitness continuum differ on language-related ERP components relative to attention-related ERP components as elicited in response to a lexical decision task. Given the considerable bodies of literature demonstrating positive associations between aerobic fitness and scholastic achievement in reading as well as attention, it was hypothesized that aerobic fitness would be positively associated with both language-related ERPs and attention-related ERP components.

2. Method

2.1. Participants

Analyses were conducted on a sample of 60 college-aged adults ($M = 19.0 \pm 1.0$ years, 45 females, 35% nonwhite) recruited from Michigan State University. Neuroelectric data was originally collected from sixty-two participants; however, two lower-fit participants were excluded from analysis due to excessively noisy data. Participants were bifurcated into lower aerobic fitness or higher aerobic fitness groups based on whether their aerobic fitness level – as assessed using VO_2max – fell below the 30th percentile or above the 70th percentile according to normative data provided by Shvartz and Reibold (1990). All participants provided written informed consent in accordance with the Michigan State University Institutional Review Board. Further, all participants completed a health history and demographics questionnaire, reported being free of any neurological diseases or physical disabilities, and indicated normal or corrected-to-normal vision. Demographic and fitness data for all participants are provided in Table 1.

2.2. Procedure

2.2.1. Aerobic fitness assessment

Aerobic fitness was assessed using a test of maximal oxygen consumption (VO_2max), which describes the physiological limit to the rate at which an individual can deliver/consume oxygen (American College of Sports Medicine, 2018). Relative peak oxygen consumption (ml/kg/min) was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400) while participants ran or walked on a motor-driven treadmill at a constant speed with incremental increases of 2.5% grade every two minutes until the participant was no longer able to maintain the exercise intensity (Pontifex et al., 2009, 2014). Aerobic fitness percentiles were extracted from normative data provided by Shvartz and Reibold (1990), accounting for both age and biological sex.

2.2.2. Language processing task

Components of language processing were assessed using the lexical decision task replicating the approach previously reported by Khalifian et al. (2016), Laszlo and Federmeier (2007a, 2007b, 2011, 2014) and Laszlo et al. (2012). In this task, participants were instructed to monitor a stream of unconnected text appearing on the screen and to respond with a button press when the text constituted a proper first name (e.g., LUKE, MAYA). When stimuli were not proper first names, stimuli were equiprobably distributed across four distinct stimulus types: words (e.g., DOG, MONEY), pseudowords (e.g., BAW, TOB), familiar acronyms (e.g., NFL, GPS), and illegal strings (e.g., ZZL, RTS).

Each stimulus was presented twice, with a delay of 0, 2, or 3 items in between the first and the second presentation. No responses were to be made to any of the critical items (words, pseudowords, acronyms, or illegal strings) – and "false alarms" (i.e., button presses to critical items) were not included as a part of the ERP analysis. Acronym familiarity was assessed using a paper and pencil post-test (Laszlo & Federmeier, 2007a, 2007b) comprising the complete list of both acronyms and illegal strings that appeared in the behavioral task. Participants were instructed to cross out any items with which they were unfamiliar. Acronyms with which participants were unfamiliar and illegal strings with which participants indicated familiarity were excluded from analysis (Laszlo & Federmeier, 2007a, 2007b). Participants reported being familiar with 81.8 ± 8.5% of acronyms and 16.1 ± 15.9% of illegal strings. The task included 750 total trials (2 presentations of 300 critical items + 150 proper names), broken up into 5 blocks of 150 trials. Stimuli were presented one at a time in white Sans Serif font directly above the fixation stimulus on a black background using PsychoPy stimulus presentation software version 1.81 (Peirce, 2009). Stimuli were presented for 500 ms with a 1450 ms response interval followed by a 1500 ms blink interval (Laszlo & Federmeier, 2011). Each of the five blocks lasted approximately eight minutes, and participants were given short breaks between each block.

2.2.3. ERP recording

EEG activity was recorded from 64 electrode sites (Fpz, Fz, FCz, Cz, CPz, Pz, POz, Oz, Fp1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/2/4/6/8, PO7/5/3/4/6/8, O1/2) arranged in an extended montage based on the International 10–10 system (Chatrian, Lettich, & Nelson, 1985) using a Neuroscan Quik-Cap (Compumedics, Inc., Charlotte, NC). Recordings were referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode. In addition, electrodes were placed above and below the left orbit and on the outer canthus of both eyes to monitor electrooculographic (EOG) activity with a bipolar recording. Continuous data were digitized at a sampling rate of 1000 Hz and amplified 500 times with a DC to 70 Hz filter using a Neuroscan SynAmps RT amplifier.

The EEG data was then imported into EEGLAB (Delorme & Makeig, 2004) and prepared for temporal ICA decomposition which enables separating artifactual activity such as eyeblinks from the underlying EEG signal to minimize the potential for these artifacts to contaminate the signal (see (Hoffmann & Falkenstein, 2008; Jung et al., 2000) for a comparison of ICA-based artifact removal relative to regression-based approaches and see (Pontifex, Gwizdala, Parks, Billinger, & Brunner, 2017) for more information on variance induced by ICA-based artifact removal). Data more than 2 s prior to the first event marker and 2 s after the final event marker were removed to restrict computation of ICA components to task-related activity. The continuous data was filtered using a 0.05 Hz high-pass 2nd order Butterworth IIR filter to remove slow drifts (Pontifex, Gwizdala, et al., 2017), and the mastoid electrodes were removed prior to ICA decomposition. ICA decomposition was performed using the extended infomax algorithm to extract sub-Gaussian components using the default settings called in the MATLAB implementation of this function in EEGLAB with the block size heuristic (floor[sqrt(EEG.pnts/3)]) drawn from MNE-Python (Gramfort et al., 2013) using a study-wise random state (Pontifex, Gwizdala, et al., 2017). Following the ICA decomposition, the eyeblink artifact components were identified using the icablinkmetrics function (Pontifex, Miskovic, & Laszlo, 2017) and the EEG data was reconstructed without

Table 1
Participant demographic and fitness characteristics (mean ± SD).

Measure	Lower Aerobic Fitness Group	Higher Aerobic Fitness Group	t	p
N	30 (28 females)	30 (17 females)		
Age (years)	19.0 ± 0.9	19.1 ± 1.1	0.5	0.6
Education (years)	13.0 ± 1.1	13.1 ± 1.4	0.2	0.8
VO_{2max} (ml/kg/min)	33.7 ± 5.5	52.6 ± 9.1	9.7	< 0.001*
VO_{2max} Percentile	13.5 ± 8.3	87.1 ± 8.7	33.5	< 0.001*

Note: VO_{2max} percentile based on normative values for VO_{2max} (Shvartz & Reibold, 1990). The t-tests reflect the differences between groups for each measure of interest. * denotes the t-test was significant at $p < 0.05$.

the eyeblink artifact. Following removal of the eye blink components, stimulus-locked epochs were created for critical items from −100 to 1000 ms around the stimulus, baseline corrected using the −100 to 0 ms pre-stimulus period and filtered using a zero phase shift low-pass filter at 30 Hz. Trials with artifact exceeding ± 100 μV were rejected. To ensure integrity of the signal, stimulus-locked epochs were visually inspected blind to the participants' fitness cohort and stimulus type prior to computing mean waveforms for each participant and stimulus type. The number of trials retained for each stimulus type was 105.0 ± 18.3 trials for names, 51.4 ± 9.0 trials for words, 53.0 ± 9.3 trials for pseudowords, 49.2 ± 8.1 trials for acronyms, and 50.9 ± 11.2 trials for illegal strings.

For the language-processing ERP components (i.e., NP150, N250, N400) elicited in response to the word, pseudoword, acronym, and illegal string stimulus types; components were evaluated using windows consistent with the extant literature which were adjusted to best capture the activity elicited from the current sample. The NP150 component was assessed as an index of orthographic decoding within a 90–175 ms window following stimulus onset. The N250 component was assessed as an index of phonological decoding within a 225–275 ms window following stimulus onset. The N400 component was assessed as an index of semantic processing within a 325–500 ms window following stimulus onset. The amplitude of each component was extracted as the mean amplitude within a 50 ms interval surrounding the peak within each respective window and the latency was evaluated as the point at which the peak amplitude occurred. The LPC was also assessed for word, pseudoword, acronym, and illegal string stimulus types and was quantified as the mean amplitude within a 600–900 ms window following stimulus onset due to the lack of a clear component peak (Laszlo et al., 2012). Finally, given the target detection nature of the task, the P3b ERP component was assessed as an index of attentional resource allocation only in response to stimuli constituting a proper first name. P3b amplitude was extracted as the mean amplitude within a 50 ms interval surrounding the peak within a 300–700 ms window following stimulus onset, and the latency was evaluated as the point at which the peak amplitude occurred (Pontifex, Parks, Henning, & Kamijo, 2015). With the well-established nature of this task and the ERP components elicited (Khalifian et al., 2016; Laszlo & Federmeier, 2007a, 2007b, 2011, 2014; Laszlo et al., 2012), analyses of language-related ERP components (i.e., NP150, N250, N400) were conducted using the midline centro-parietaloccipital electrodes (CZ, CPZ, PZ, POZ) while analyses of attention-related ERP components (i.e., LPC & P3b) were conducted using the midline centroparietal-occipital electrodes (CPZ, PZ, POZ, OZ) in order to capture the topographic maxima of these components.

2.2.4. Experimental protocol

Using a cross-sectional design, participants visited the laboratory on two separate days. On the first, participants signed an informed consent, completed a Health History and Demographics Questionnaire and the Physical Activity Readiness Questionnaire (Thomas, Reading, & Shephard, 1992), and completed the aerobic fitness assessment. Participants who fell at or above the 70th percentile or at or below the 30th percentile for aerobic fitness were invited to return for a second day of testing. On the second day (16.5 ± 8.9 days later), participants were outfitted with an EEG electrode cap to record neuroelectric activity and then completed the language processing task. Participants were seated in a sound-attenuated testing chamber approximately 1 m away from the computer monitor. Before beginning the five experimental blocks, participants were given an explanation of the task and performed a brief practice block, consisting of example stimuli similar to those used in the task itself. A fixation stimulus (a cartoon face; Khalifian et al., 2016) was present on the screen throughout the entire experiment, and in order to minimize blinks and eye movements, participants were told to try to blink only between presentations of each stimulus – indicated on the screen by an image of the cartoon face blinking its eyes.

2.3. Statistical analysis

Analyses were conducted with α = 0.05 using Benjamini-Hochberg false discovery rate control = 0.05 for post-hoc decompositions. Analysis of behavioral performance was conducted using Mann-Whitney U-tests to examine differences between groups for response accuracy given the non-normal distribution and independent-samples t-tests were used to examine differences between groups for mean reaction time. Analyses of ERP components (NP150, N250, N400, and LPC) in response to non-target stimuli were conducted using a 2 (Group: lower aerobic fitness, higher aerobic fitness) × 4 (Type: words, pseudowords, acronyms, illegal strings) × 2 (Presentation: first presentation, second presentation) univariate multi-level model. Analysis of the P3b ERP component in response to the target stimuli (i.e., names) was conducted using a univariate multi-level model with Group (lower aerobic fitness, higher aerobic fitness) entered as a factor. Each multi-level model was run separately for amplitude and latency. Given the nested repeated measures structure of the data, a multi-level model approach was used as it allowed for modeling the random intercept for each Participant and Electrode Channel thus increasing the power to detect fixed effects (see (Misangyi, LePine, Algina, & Goeddeke, 2006) for a comparison of multi-level modeling to repeated-measures ANOVA). Analyses were performed using the lme4 (Bates, Mächler, Bolker, & Walker, 2015), lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017), and emmeans (Lenth, Love, & Herve, 2017) packages in R Version 3.4.1 (R Core Team, 2013) with Kenward-Roger degrees of freedom approximations. For each inferential finding, Cohen's f^2 and d with 95% confidence intervals were computed as standardized measures of effect size, using appropriate variance corrections for between-subject (d_s) and within-subject (d_{rm}) comparisons (Lakens, 2013). Given a sample size of 60 participants and a beta of 0.20 (i.e., 80% power), the present research design theoretically had sufficient sensitivity to detect differences between groups exceeding $d_s = 0.74$ and differences within groups exceeding $d_{rm} = 0.37$ (with a two-sided alpha) as computed using G*Power 3.1.2 (Faul, Erdfelder, Lang, & Buchner, 2007).

3. Results

3.1. Behavioral data

Participants were instructed to press a button only when names were present on the screen. Thus, button presses for names were classified as "hits," and button presses for critical items (words, pseudowords, acronyms, or illegal strings) were classified as "false alarms." The overall hit rate was 90.3% (~136/150 names), and the overall false alarm rate was 2.6% (~16/600 critical items). Analysis revealed no differences between groups for either the overall hit rate or the false alarm rate, Mann-Whitney $U's \le 382.0$, $Z's \le 1.8$, $p \ge 0.07$, $r \le 0.23$. Similarly, no differences between groups were observed for mean reaction time to the names stimuli, $t(58) = 1.3$, $p = 0.2$, $d_s = 0.34$ [95% CI: −0.17 to 0.84].

3.2. Orthographic decoding

Analysis of NP150 amplitude revealed a main effect of stimulus Type, $F(3, 1707) = 21.3$, $p < 0.001$, $f^2 = 2.67$ [95% CI: 1.62–5.13]. Post-hoc comparisons revealed that NP150 amplitude was more negative for words and pseudowords than for acronyms and illegal strings, $t's(1706) \ge 4.8$, $p's < 0.001$, $d_{rm}'s \ge 0.32$ [95% CI: 0.19–0.65], see Fig. 1. No main effects or interactions involving Group were observed, $F's(3, 1707) \le 0.5$, $p's \ge 0.6$, $f^2's \le 0.07$ [95% CI: 0.00–0.21].

Analysis of NP150 latency revealed no main effects or interactions $F's(1, 55) \le 1.7$, $p's \ge 0.2$, $f^2's \le 0.52$ [95% CI: 0.00–1.10].

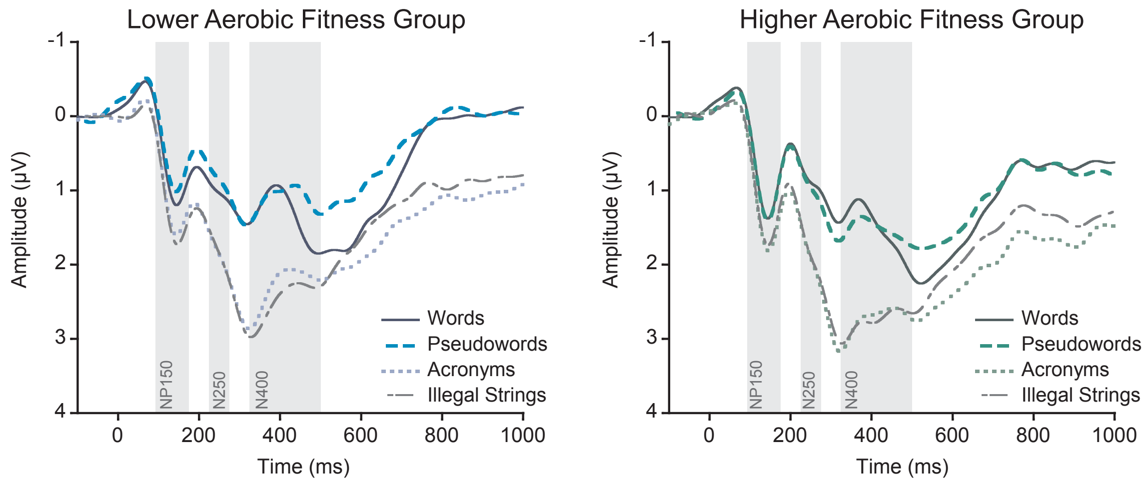

Fig. 1. Illustration of the grand mean stimulus-locked waveforms for the lower- (left) and higher- (right) aerobic fitness groups as a function of stimulus type (words, pseudowords, acronyms, and illegal strings). Each waveform is collapsed across presentation (first and second presentation) and midline centro-parietaloccipital electrodes (CZ, CPZ, PZ, POZ). The component windows are indicated by the shaded areas.

3.3. Phonological decoding

Analysis of N250 amplitude revealed a main effect of stimulus Type, $F(3, 1708) = 38.4, p < 0.001, f^2 = 2.74$ [95% CI: 1.67–5.26]. Post-hoc comparisons revealed that N250 amplitude was more negative for words and pseudowords than for acronyms and illegal strings, t's (1706) ≥ 7.1, p's < 0.001, d_{rm}'s ≥ 0.54 [95% CI: 0.40–0.85], see Fig. 1. No main effects or interactions involving Group were observed, F's (3, 1706) ≤ 0.8, p's ≥ 0.4, f^2's ≤ 0.02 [95% CI: 0.00–0.09].

Analysis of N250 latency revealed a main effect of stimulus Type, F (3, 1709) = 4.2, $p = 0.006$, $f^2 = 1.36$ [95% CI: 0.74–2.67]. Post-hoc comparisons revealed that N250 latency was later for pseudowords relative to acronyms and illegal strings, t's (1709) ≥ 3.0, p's < 0.003, d_{rm}'s ≥ 0.25 [95% CI: 0.09–0.46]. No main effects or interactions involving Group were observed, F's (3, 1706) ≤ 0.8, p's ≥ 0.5, f^2's ≤ 0.27 [95% CI: 0.04–0.62].

3.4. Semantic processing

Analysis of N400 amplitude revealed a main effect of stimulus Type, $F(3, 1708) = 53.3, p < 0.001, f^2 = 2.80$ [95% CI: 1.71–5.38]. Post-hoc comparisons revealed that N400 amplitude was more negative for words and pseudowords than for acronyms and illegal strings, t's (1706) ≥ 7.8, p's < 0.001, d_{rm}'s ≥ 0.64 [95% CI: 0.47–1.00], see Fig. 1. There was also a main effect of Presentation, F (1, 3926) = 55.5, $p < 0.001$, $d_{rm} = 0.41$ [95% CI: 0.30–0.52], such that N400 amplitude was more negative for first presentations than for second presentations. However, no interaction between stimulus Type and Presentation was observed, F (3, 1706) = 0.6, $p = 0.6$, $f^2 = 0.02$ [95% CI: 0.00–0.10]. Similarly, no main effects or interactions involving Group were observed, F's (3, 1706) ≤ 0.9, p's ≥ 0.4, f^2's ≤ 0.01 [95% CI: 0.00–0.06].

Analysis of N400 latency revealed a main effect of stimulus Type, F (3, 1709) = 32.4, $p < 0.001$, $f^2 = 2.39$ [95% CI: 1.43–4.60], which was superseded by an interaction of stimulus Type × Presentation, F (3, 1706) = 3.3, $p = 0.02$, $f^2 = 0.24$ [95% CI: 0.03–0.57]. Post-hoc decomposition of this interaction was conducted by examining stimulus Type within each Presentation. For the first presentation, N400 latency was earlier for words and pseudowords relative to acronyms and illegal strings, t's (833) ≥ 5.0, p's < 0.001, d_{rm}'s ≥ 0.66 [95% CI: 0.40–1.25]. For the second presentation, N400 latency was earlier for words relative to pseudowords, acronyms, and illegal strings, t's (826) ≥ 3.0, p's < 0.003, d_{rm}'s ≥ 0.45 [95% CI: 0.15–1.23]. N400 latency was also earlier at the second presentation for pseudowords relative to illegal strings, t (826) = 3.3, $p < 0.001$, $d_{rm} = 0.50$ [95% CI: 0.20–0.79]. There was no statistical difference at the second presentation between N400 latency to acronyms and either pseudowords or illegal strings following false discovery rate control (Benjamini-Hochberg critical alpha = 0.032), t's (824) ≤ 2.0, p's = 0.049, d_{rm}'s ≤ 0.30 [95% CI: −0.07 to 0.60]. No main effects or interactions involving Group were observed, F's (3, 1706) ≤ 1.4, p's ≥ 0.2, f^2's ≤ 0.03 [95% CI: 0.00–0.13].

3.5. Attentional processing

Analysis of LPC amplitude revealed smaller amplitude for the lower aerobic fitness group relative to the higher aerobic fitness group, F (1, 55) = 5.2, $p = 0.026$, $d_s = 0.61$ [95% CI: 0.07–1.14], see Fig. 2. Further, a main effect of stimulus Type was observed, F (3, 1708) = 29.4, $p < 0.001, f^2 = 2.25$ [95% CI: 1.34–4.34], with post-hoc comparisons indicating that LPC amplitude was greater for words and pseudowords relative to acronyms and illegal strings, t's (1706) ≥ 4.9, p's < 0.001, d_{rm}'s ≥ 0.5 [95% CI: 0.30–0.96], see Fig. 1.

Analysis of P3b amplitude in response to the behavioral target name trials revealed smaller amplitude for the lower aerobic fitness group relative to the higher aerobic fitness group, F (1, 58) = 4.5, $p = 0.039$, $d_s = 0.55$ [95% CI: 0.03–1.06], see Fig. 2.

Analysis of P3b latency revealed no differences between the lower and higher aerobic fitness group, F (1, 58) = 0.3, $p = 0.6$, $d_s = 0.14$ [95% CI: −0.37 to 0.65].

4. Discussion

The aim of the present investigation was to determine the extent to which individuals at the extremes of the aerobic fitness continuum differ on neuroelectric indices of both language and attentional processing. In contrast to our a priori hypothesis that individuals in the lower aerobic fitness group would exhibit smaller amplitude relative to the higher aerobic fitness group for both language- and attention-related ERP components, findings revealed a positive association with aerobic fitness only for ERP components associated with attentional processing (i.e., the LPC and P3b). ERP components associated with language processing (i.e., the NP150, N250, and N400) were not observed to differ between individuals at the extremes of the aerobic fitness continuum, and no differences in behavioral task performance were observed as a function of aerobic fitness.

Although no fitness-related differences were observed with regard to language-processing-related ERP components, it is important to acknowledge the efficacy of the lexical decision task used within the present investigation. Indeed, behavioral performance on the task was

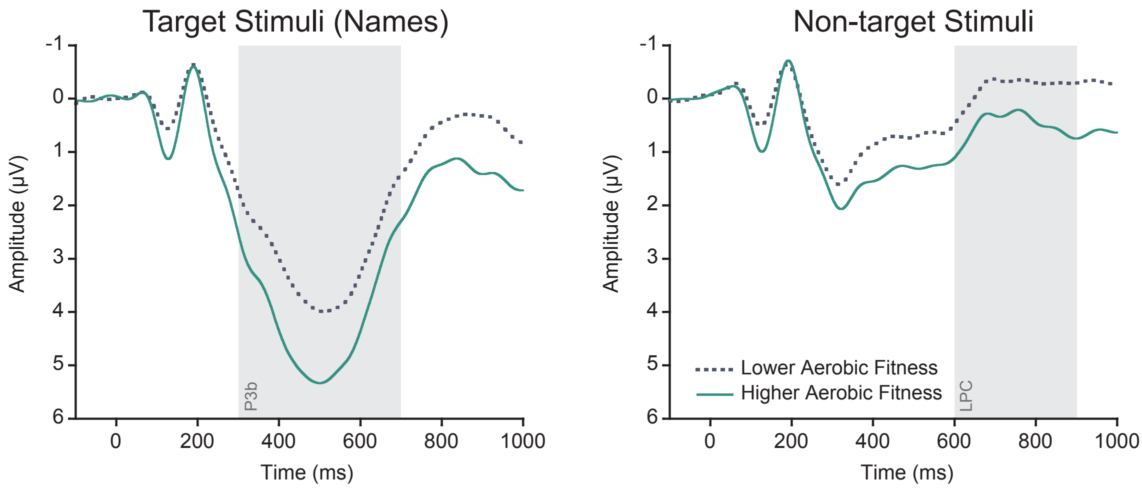

Fig. 2. Illustration of the grand mean stimulus-locked waveform for the target stimulus type (names) and non-target stimuli (words, pseudowords, acronyms, and illegal strings) as a function of aerobic fitness group. Each waveform is collapsed across midline centroparietal-occipital electrodes (CPZ, PZ, POZ, OZ) and the waveform for the non-target stimuli is also collapsed across presentation (first and second presentation). The component windows are indicated by the shaded areas.

exceptionally high, indicating that participants were actively engaged in the task and were appropriately attending to the stimuli. Further, the present investigation largely replicated the extant literature with regard to modulations of language-processing-related ERP components in response to lexical relative to non-lexical stimuli (Khalifian et al., 2016; Laszlo & Federmeier, 2007a, 2007b, 2011, 2014; Laszlo et al., 2012). Specifically, semantic processing — as indexed by the amplitude of the N400 ERP component — was greater for lexical stimuli (words and pseudowords) than for non-lexical stimuli (acronyms and illegal strings). Additionally, the prominent N400 repetition effect was also replicated with greater semantic processing for the first presentation of the stimulus than for the second presentation (Barber & Kutas, 2007; Bentin, McCarthy, & Wood, 1985; Laszlo et al., 2012; Rugg, 1990). Although lexical differences in the NP150 and N250 are not typically observed or at least have not been commonly reported/investigated, speculatively, such findings within the present investigation may be attributed to the high-functioning college-aged adult population who may have been able to more rapidly begin engaging lexical processing. In such a case, the nature of ERP components, which reflect the summation of activity at the surface of the scalp, may then have enabled the temporal overlap of these processes.

The present investigation also replicated the well-established finding that aerobic fitness is positively associated with the amplitude of the P3b ERP component. Specifically, lower aerobically fit individuals relative to higher aerobically fit individuals exhibit poorer allocation of attentional resources in support of context updating in response to simple stimulus-discrimination oddball paradigms (Hillman et al., 2005; Pontifex et al., 2009). Novel to this investigation was the finding that such aerobic fitness differences also extend to another P3-like component elicited by the same task: the LPC. In the case of the lexical decision task used by this investigation, the LPC manifests during the period following the N400 — with the amplitude believed to reflect the allocation of attentional resources in support of determining the lexical meaningfulness of the letter array (Laszlo et al., 2012). Providing further support for the assertion that P3b amplitude and LPC amplitude reflect similar attentional constructs, P3 amplitude for target stimuli and LPC amplitude collapsed across non-target stimuli were well correlated: $r = 0.55$ [95% CI: 0.33–0.71], $p < 0.001$. Interestingly, when viewed within the framework that the P3b, LPC, and P600 cluster within the same family of conceptually similar attention- and memory- related processes (Coulson et al., 1998; Sassenhagen et al., 2014), the present findings appear to rectify the extant literature with regard to the association between fitness and semantic processing as indexed by the N400.

Although the differences in N400 amplitude between higher- and lower-fit individuals as observed by Scudder et al. (2014) stand in contrast to the absence of N400 findings observed within the present investigation, the nature of the sentence processing task used by Scudder and colleagues may have enabled attention-related effects to manifest within the N400 (Kutas & Federmeier, 2011; Payne & Federmeier, 2018). That is, previous investigations have observed that the progressive semantic and syntactic processing — naturally occurring within sentence processing tasks as meaning is built up with each successive word presentation — can modulate N400 amplitude for single words nested within the context of a sentence (Brouwer & Crocker, 2017; Meltzer & Braun, 2013; Payne, Lee, & Federmeier, 2015). Similarly, sentence processing tasks which manipulate attentional demands have been observed to modulate N400 amplitude (Kemp et al., 2019). Thus, if aerobic fitness impacts upon the attentional components associated with syntactic processing (as indexed by the P600) as observed by Scudder et al. (2014), then it follows that semantic processing (as indexed by the N400) would be impacted as well. In contrast, as Magnié et al. (2000) observed no differences in attentional processing (as indexed by P3b) between their higher- and lower- aerobically fit groups, it is perhaps unsurprising that no differences in semantic processing in response to the sentence processing task were observed either. Accordingly, the nature of the task utilized by the present investigation enables clear separation of these potential interactive effects and provides a framework by which the extant literature in this area appear consistent in their findings. Thus, these findings suggest that aerobic fitness relates to aspects of attentional processing, but does not specifically impact neural indices of word level language processing. Together, these findings introduce the possibility that the relationship between aerobic fitness and scholastic achievement in reading may be driven by attentional characteristics rather than differences in actual language processing. Indeed, the allocation of attentional resources in support of context updating — as indexed by the P3b ERP component — is well correlated with superior reading achievement and reading comprehension (Commodari & Guarnera, 2005; Hillman, Pontifex, et al., 2012; Rabiner & Coie, 2000; Rowe & Rowe, 1992).

However, it is important to emphasize the speculative nature of such an assertion given that the present investigation did not also collect a measure of reading achievement. Thus, further research is necessary to incorporate measures of reading achievement alongside neuroelectric indices of attention and language processing at multiple levels of representation (word, sentence, discourse) and modality (written text versus speech) (e.g., Ng, Payne, Steen, Stine-Morrow, &

Federmeier, 2017; Ng, Payne, Stine-Morrow, & Federmeier, 2018) to better understand the structure of the relationships with aerobic fitness across language proficiency levels. Similarly, while the framework clustering together the P3b, LPC, and P600 components appears to create a compelling interpretation of the extant literature, it may also be that there is a developmental window in which aerobic fitness and neural indices of language processing are related. Indeed, given the college-aged population, the lack of observing differences in language processing within the present investigation — and that of Magnié et al. (2000) — may simply manifest as language proficiency was sufficiently developed so as to be robust to potential impairments associated with poorer aerobic fitness. However, despite such developmental ceilings in language proficiency; it is important to note that even within adolescents and college-aged young adults, higher levels of engagement in vigorous physical activity and/or participation in sport – both of which are associated with higher levels of aerobic fitness – are associated with higher GPA in college students and superior performance on standardized achievement tests (Kwak et al., 2009; Ruiz-Ariza et al., 2017; Vasold et al., 2019; Welk et al., 2010). Further research is thus necessary to examine the relationship between aerobic fitness and language processing at various developmental stages to better understand how aerobic fitness may alter maturational processes in language development and other aspects of cognition. Future research in this area should also seek to characterize baseline language ability, exposure to print, and word knowledge to ensure similar levels of language ability across fitness groups. Given that the present investigation utilized a sample of high-functioning college-aged adults enrolled at the same university with no differences between groups in the number of years of education, it is unlikely that this presents as a confound within the current investigation. However, such an understanding has greater relevance when investigating other developmental stages prior to young adulthood since language processes may still be developing. Finally, as the present investigation utilized a cross-sectional approach, future research is necessary to understand how changes in aerobic fitness manifest in changes to neuroelectric indices of language processing and attention/memory over time.

Collectively, utilizing a well-powered sample of college-aged young adults, the present investigation observed that orthographic, phonological, and semantic aspects of word level language processing do not differentially manifest across the extremes of the aerobic fitness continuum. Rather, aerobic fitness appears to relate to aspects of attention and memory such that poorer aerobic fitness is associated with reductions in attentional processing in support of context updating. Thus, it may be that aerobic fitness-related differences in reading achievement in adults result from attentional processes rather than from acting upon specific word level language processes. Nevertheless, it is important to note that regardless of the mechanism(s) by which superior literacy occurs, such abilities have implications that extend well beyond the classroom environment. Indeed, superior language ability and/or higher levels of literacy are positively associated with a myriad of outcomes including educational attainment, employment status, and income (Reder, 2013). In addition, superior language and literacy abilities are related to an attenuated risk of memory loss and/or general cognitive decline as adults age, as well as to higher levels of health literacy – and thus, are linked to positive health outcomes (Chin et al., 2011; Manly, Schupf, Tang, & Stern, 2005; Manly, Touradji, Tang, & Stern, 2003; Payne, Gao, Noh, Anderson, & Stine-Morrow, 2012). Accordingly, understanding those mechanisms which are important for supporting and enhancing literacy are essential for optimizing cognitive health and effective function not only in schools but also in the workplace and health care settings.

5. Statement of significance

These findings introduce the possibility that the relationship between aerobic fitness and scholastic achievement in reading may be driven by attentional characteristics rather than differences in actual language processing.

CRediT authorship contribution statement

Madison C. Chandler: Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Amanda L. McGowan:** Investigation, Writing - review & editing. **Brennan R. Payne:** Validation, Resources, Writing - review & editing. **Amanda Hampton Wray:** Validation, Writing - review & editing. **Matthew B. Pontifex:** Methodology, Software, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

None.

Acknowledgments

Support for the preparation of this manuscript was provided by a fellowship awarded to M. Chandler through the College of Education at Michigan State University.

References

2018 Physical Activity Guidelines Advisory Committee (2018). 2018 Physical activity guidelines advisory committee scientific report. Washington, DC.

American College of Sports Medicine (2018). *ACSM's guidelines for exercise testing and prescription* (10th ed.). New York: Lippincott Williams & Wilkins.

Araújo, S., Bramão, I., Faísca, L., Petersson, K. M., & Reis, A. (2012). Electrophysiological correlates of impaired reading in dyslexic pre-adolescent children. *Brain and Cognition, 79*(2), 79–88. https://doi.org/10.1016/j.bandc.2012.02.010.

Barber, H. A., & Kutas, M. (2007). Interplay between computational models and cognitive electrophysiology in visual word recognition. *Brain Research Reviews, 53*(1), 98–123. https://doi.org/10.1016/j.brainresrev.2006.07.002.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Bentin, S., McCarthy, G., & Wood, C. C. (1985). Event-related potentials, lexical decision and semantic priming. *Electroencephalography and Clinical Neurophysiology, 60*(4), 343–355. https://doi.org/10.1016/0013-4694(85)90008-2.

Brouwer, H., & Crocker, M. W. (2017). On the proper treatment of the N400 and P600 in language comprehension. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.01327.

Castelli, D. M., Hillman, C. H., Buck, S. M., & Erwin, H. E. (2007). Physical fitness and academic achievement in third- and fifth-grade students. *Journal of Sport & Exercise Psychology, 29*, 239–252.

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity. *American Journal of EEG Technology, 25*, 83–92. https://doi.org/10.1080/00029238.1985.11080163.

Chauncey, K., Holcomb, P. J., & Grainger, J. (2008). Effects of stimulus font and size on masked repetition priming: An event-related potentials (ERP) investigation. *Language and Cognitive Processes, 23*(1), 183–200. https://doi.org/10.1080/01690960701579839.

Chin, J., Stine-Morrow, E. A. L., Morrow, D., Gao, X., Conner-Garcia, T., Graumlich, J. F., & Murray, M. D. (2011). The effects of domain general and health knowledge in processing general and health texts among older adults with hypertension. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 55*(1), 147–151. https://doi.org/10.1177/1071181311551031.

Chu, C.-H., Chen, F.-T., Pontifex, M. B., Sun, Y., & Chang, Y.-K. (2016). Health-related physical fitness, academic achievement, and neuroelectric measures in children and adolescents. *International Journal of Sport and Exercise Psychology,* 1–16. https://doi.org/10.1080/1612197X.2016.1223420.

Coch, D., & Holcomb, P. J. (2003). The N400 in beginning readers. *Developmental Psychobiology, 43*(2), 146–166. https://doi.org/10.1002/dev.10129.

Coe, D. P., Pivarnik, J. M., Womack, C. J., Reeves, M. J., & Malina, R. M. (2012). Health-related fitness and academic achievement in middle school students. *The Journal of Sports Medicine and Physical Fitness, 52*(6), 654–660.

Coe, D. P., Pivarnik, J. M., Womak, C. J., Reeves, M. J., & Malina, R. M. (2006). Effect of physical education and activity levels on academic achievement in children. *Medical & Science in Sports & Exercise, 38*, 1515–1519. https://doi.org/10.1249/01.mss.0000227537.13175.1b.

Commodari, E., & Guarnera, M. (2005). Attention and reading skills. *Perceptual and Motor Skills, 100*(2), 375–386. https://doi.org/10.2466/pms.100.2.375-386.

Coulson, S., King, J. W., & Kutas, M. (1998). Expect the unexpected: Event-related brain response to morphosyntactic violations. *Language and Cognitive Processes, 13*(1), 21–58. https://doi.org/10.1080/016909698386582.

Curran, T., Tucker, D. M., Kutas, M., & Posner, M. I. (1993). Topography of the N400: Brain electrical activity reflecting semantic expectancy. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 88*(3), 188–209. https://doi.org/10.1016/0168-5597(93)90004-9.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods, 134*, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Eddy, M. D., Grainger, J., Holcomb, P. J., Mitra, P., & Gabrieli, J. D. E. (2014). Masked priming and ERPs dissociate maturation of orthographic and semantic components of visual word recognition in children. *Psychophysiology, 51*(2), 136–141. https://doi.org/10.1111/psyp.12164.

Esteban-Cornejo, I., Tejero-González, C. M., Martinez-Gomez, D., Del-Campo, J., González-Galo, A., Padilla-Moledo, C., ... Veiga, O. L. (2014). Independent and combined influence of the components of physical fitness on academic performance in youth. *The Journal of Pediatrics, 165*(2), 306–312.e2. https://doi.org/10.1016/j.jpeds.2014.04.044.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 29*, 175–191. https://doi.org/10.3758/BF03193146.

Fedewa, A. L., & Ahn, S. (2011). The effects of physical activity and physical fitness on children's achievement and cognitive outcomes: A meta-analysis. *Research Quarterly for Exercise and Sport, 82*(3), 521–535.

Frisch, S., Kotz, S. A., von Cramon, D. Y., & Friederici, A. D. (2003). Why the P600 is not just a P300: The role of the basal ganglia. *Clinical Neurophysiology, 114*(2), 336–340. https://doi.org/10.1016/S1388-2457(02)00366-8.

Grainger, J., & Holcomb, P. J. (2009). Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass, 3*(1), 128–156. https://doi.org/10.1111/j.1749-818X.2008.00121.x.

Gramfort, A., Luessi, M., Larson, E., Engemann, D. A., Strohmeier, D., Brodbeck, C., ... Hämäläinen, M. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience, 7*, 1–13. https://doi.org/10.3389/fnins.2013.00267.

Henderson, L. M., Baseler, H. A., Clarke, P. J., Watson, S., & Snowling, M. J. (2011). The N400 effect in children: Relationships with comprehension, vocabulary and decoding. *Brain and Language, 117*(2), 88–99. https://doi.org/10.1016/j.bandl.2010.12.003.

Hillman, C. H., Castelli, D. M., & Buck, S. M. (2005). Aerobic fitness and neurocognitive function in healthy preadolescent children. *Medicine & Science in Sports & Exercise, 37*, 1967–1974.

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience, 9*, 58–65. https://doi.org/10.1038/nrn2298.

Hillman, C. H., Kamijo, K., & Pontifex, M. B. (2012). The relation of ERP indices of exercise to brain health and cognition. In H. Boecker, C. H. Hillman, L. Scheef, & H. K. Strüder (Eds.), Functional neuroimaging in exercise and sport sciences (pp. 419–446). https://doi.org/10.1007/978-1-4614-3293-7_18.

Hillman, C. H., Pontifex, M. B., Motl, R. W., O'Leary, K. C., Johnson, C. R., Scudder, M. R., ... Castelli, D. M. (2012). From ERPs to academics. *Developmental Cognitive Neuroscience, 2*(Suppl 1), S90–S98. https://doi.org/10.1016/j.dcn.2011.07.004.

Hoffmann, S., & Falkenstein, M. (2008). Correction of eye blink artefacts in the EEG: A comparison of two prominent methods. *PLOS One, 3*, 1–11. https://doi.org/10.1371/journal.pone.0003004.

Holcomb, P. J., & Grainger, J. (2006). On the time course of visual word recognition: An event-related potential investigation using masked repetition priming. *Journal of Cognitive Neuroscience, 18*(10), 1631–1643. https://doi.org/10.1162/jocn.2006.18.10.1631.

Janak, J. C., Gabriel, K. P., Oluyomi, A. O., Peréz, A., Kohl, H. W., & Kelder, S. H. (2014). The association between physical fitness and academic achievement in Texas state house legislative districts: An ecologic study. *Journal of School Health, 84*(8), 533–542. https://doi.org/10.1111/josh.12176.

Jung, T., Makeig, S., Humphries, C., Lee, T., McKeown, M. J., Iragui, V., & Sejnowski, T. J. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology, 37*, 163–178. https://doi.org/10.1111/1469-8986.3720163.

Kemp, A., Eddins, D., Shrivastav, R., & Hampton Wray, A. (2019). Effects of task difficulty on neural processes underlying semantics: An event-related potentials study. *Journal of Speech, Language, and Hearing Research, 62*(2), 367–386. https://doi.org/10.1044/2018_JSLHR-H-17-0396.

Khalifian, N., Stites, M. C., & Laszlo, S. (2016). Relationships between event-related potentials and behavioral and scholastic measures of reading ability: A large-scale, cross-sectional study. *Developmental Science, 19*(5), 723–740. https://doi.org/10.1111/desc.12329.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62*(1), 621–647. https://doi.org/10.1146/annurev.psych.093008.131123.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13.

Kwak, L., Kremers, S. P. J., Bergman, P., Ruiz, J. R., Rizzo, N. S., & Sjöström, M. (2009). Associations between physical activity, fitness, and academic achievement. *The Journal of Pediatrics, 155*(6), 914–918.e1. https://doi.org/10.1016/j.jpeds.2009.06.019.

Lachmann, T., Berti, S., Kujala, T., & Schröger, E. (2005). Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. *International Journal of Psychophysiology, 56*(2), 105–120. https://doi.org/10.1016/j.ijpsycho.2004.11.005.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*(863), 1–12. https://doi.org/10.3389/fpsyg.2013.00863.

Landi, N., & Perfetti, C. A. (2007). An electrophysiological investigation of semantic and phonological processing in skilled and less-skilled comprehenders. *Brain and Language, 102*(1), 30–45. https://doi.org/10.1016/j.bandl.2006.11.001.

Laszlo, S., & Federmeier, K. D. (2007a). Better the DVL you know: Acronyms reveal the contribution of familiarity to single-word reading. *Psychological Science, 18*(2), 122–126. https://doi.org/10.1111/j.1467-9280.2007.01859.x.

Laszlo, S., & Federmeier, K. D. (2007b). The acronym superiority effect. *Psychonomic Bulletin & Review, 14*(6), 1158–1163. https://doi.org/10.3758/BF03193106.

Laszlo, S., & Federmeier, K. D. (2011). The N400 as a snapshot of interactive processing: Evidence from regression analyses of orthographic neighbor and lexical associate effects. *Psychophysiology, 48*(2), 176–186. https://doi.org/10.1111/j.1469-8986.2010.01058.x.

Laszlo, S., & Federmeier, K. D. (2014). Never seem to find the time: Evaluating the physiological time course of visual word recognition with regression analysis of single-item event-related potentials. *Language, Cognition and Neuroscience, 29*(5), 642–661. https://doi.org/10.1080/01690965.2013.866259.

Laszlo, S., & Sacchi, E. (2015). Individual differences in involvement of the visual object recognition system during visual word recognition. *Brain and Language, 145–146*, 42–52. https://doi.org/10.1016/j.bandl.2015.03.009.

Laszlo, S., Stites, M., & Federmeier, K. D. (2012). Won't get fooled again: An event-related potential study of task and repetition effects on the semantic processing of items without semantics. *Language and Cognitive Processes, 27*(2), 257–274. https://doi.org/10.1080/01690965.2011.606667.

Lau, E. F., Holcomb, P. J., & Kuperberg, G. R. (2012). Dissociating N400 effects of prediction from association in single-word contexts. *Journal of Cognitive Neuroscience, 25*(3), 484–502. https://doi.org/10.1162/jocn_a_00328.

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (De)constructing the N400. *Nature Reviews Neuroscience, 9*(12), 920–933. https://doi.org/10.1038/nrn2532.

Leckey, M., & Federmeier, K. D. (2019). The P3b and P600(s): Positive contributions to language comprehension. *Psychophysiology,* e13351. https://doi.org/10.1111/psyp.13351.

Lenth, R., Love, J., & Herve, M. (2017). emmeans: Estimated marginal means, aka least-squares means. Retrieved from https://github.com/rvlenth/emmeans.

Magnié, M. N., Bermon, S., Martin, F., Madany-Lounis, M., Suisse, G., Muhammad, W., & Dolisi, C. (2000). P300, N400, aerobic fitness, and maximal aerobic exercise. *Psychophysiology, 37*(3), 369–377.

Manly, J. J., Schupf, N. S., Tang, M.-X., & Stern, Y. (2005). Cognitive decline and literacy among ethnically diverse elders. *Journal of Geriatric Psychiatry and Neurology, 18*(4), 213–217. https://doi.org/10.1177/0891988705281868.

Manly, J. J., Touradji, P., Tang, M.-X., & Stern, Y. (2003). Literacy and memory decline among ethnically diverse elders. *Journal of Clinical and Experimental Neuropsychology, 25*(5), 680–690. https://doi.org/10.1076/jcen.25.5.680.14579.

Meltzer, J. A., & Braun, A. R. (2013). P600-like positivity and left anterior negativity responses are elicited by semantic reversibility in nonanomalous sentences. *Journal of Neurolinguistics, 26*(1), 129–148. https://doi.org/10.1016/j.jneuroling.2012.06.001.

Misangyi, V. F., LePine, J. A., Algina, J., & Goeddeke, F. (2006). The adequacy of repeated-measures regression for multilevel research: Comparisons With repeated-measures ANOVA, multivariate repeated-measures ANOVA, and multilevel modeling across various multilevel research designs. *Organizational Research Methods, 9*(1), 5–28. https://doi.org/10.1177/1094428105283190.

Ng, S., Payne, B. R., Steen, A. A., Stine-Morrow, E. A. L., & Federmeier, K. D. (2017). Use of contextual information and prediction by struggling adult readers: Evidence from reading times and event-related potentials. *Scientific Studies of Reading, 21*(5), 359–375. https://doi.org/10.1080/10888438.2017.1310213.

Ng, S., Payne, B. R., Stine-Morrow, E. A. L., & Federmeier, K. D. (2018). How struggling adult readers use contextual information when comprehending speech: Evidence from event-related potentials. *International Journal of Psychophysiology, 125*, 1–9. https://doi.org/10.1016/j.ijpsycho.2018.01.013.

ParticipACTION. (2018). The ParticipACTION Report Card on Physical Activity for Children and Youth. Retrieved from https://www.participaction.com/en-ca/thought-leadership/report-card/2018.

Payne, B. R., & Federmeier, K. D. (2018). Contextual constraints on lexico-semantic processing in aging: Evidence from single-word event-related brain potentials. *Brain Research, 1687*, 117–128. https://doi.org/10.1016/j.brainres.2018.02.021.

Payne, B. R., Gao, X., Noh, S. R., Anderson, C. J., & Stine-Morrow, E. A. L. (2012). The effects of print exposure on sentence processing and memory in older adults: Evidence for efficiency and reserve. *Aging, Neuropsychology, and Cognition, 19*(1–2), 122–149. https://doi.org/10.1080/13825585.2011.628376.

Payne, B. R., Lee, C.-L., & Federmeier, K. D. (2015). Revisiting the incremental effects of context on word processing: Evidence from single-word event-related brain potentials. *Psychophysiology, 52*(11), 1456–1469. https://doi.org/10.1111/psyp.12515.

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics, 2*, 10. https://doi.org/10.3389/neuro.11.010.2008.

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*, 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.

Pontifex, M. B., Gwizdala, K. L., Parks, A. C., Billinger, M., & Brunner, C. (2017). Variability of ICA decomposition may impact EEG signals when used to remove eyeblink artifacts. *Psychophysiology, 54*(3), 386–398. https://doi.org/10.1111/psyp.12804.

Pontifex, M. B., Hillman, C. H., & Polich, J. (2009). Age, physical fitness, and attention: P3a and P3b. *Psychophysiology, 46*(2), 379–387. https://doi.org/10.1111/j.1469-8986.2008.00782.x.

Pontifex, M. B., Miskovic, V., & Laszlo, S. (2017). Evaluating the efficacy of fully automated approaches for the selection of eyeblink ICA components. *Psychophysiology, 54*(5), 780–791. https://doi.org/10.1111/psyp.12827.

Pontifex, M. B., Parks, A. C., Henning, D. A., & Kamijo, K. (2015). Single bouts of exercise selectively sustain attentional processes. *Psychophysiology, 52*(5), 618–625. https://doi.org/10.1111/psyp.12395.

Pontifex, M. B., Parks, A. C., O'Neil, P. C., Egner, A. R., Warning, J. T., Pfeiffer, K. A., & Fenn, K. M. (2014). Poorer aerobic fitness relates to reduced integrity of multiple memory systems. *Cognitive, Affective, & Behavioral Neuroscience, 14*(3), 1132–1141. https://doi.org/10.3758/s13415-014-0265-z.

Pontifex, M. B., Raine, L. B., Johnson, C. R., Chaddock, L., Voss, M. W., Cohen, N. J., ... Hillman, C. H. (2011). Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *Journal of Cognitive Neuroscience, 23*(6), 1332–1345. https://doi.org/10.1162/jocn.2010.21528.

R Core Team (2013). R: A Language and Environment for Statistical Computing. Retrieved from http://www.R-project.org/.

Rabiner, D., & Coie, J. D. (2000). Early attention problems and children's reading achievement: A longitudinal investigation. *Journal of the American Academy of Child & Adolescent Psychiatry, 39*(7), 859–867. https://doi.org/10.1097/00004583-200007000-00014.

Reder, S. (2013). Lifelong and life-wide adult literacy development. *Perspectives on Language and Literacy Baltimore, 39*(2), 18–21.

Rowe, K. J., & Rowe, K. S. (1992). The relationship between inattentiveness in the classroom and reading achievement (Part B): An explanatory study. *Journal of the American Academy of Child & Adolescent Psychiatry, 31*(2), 357–368. https://doi.org/10.1097/00004583-199203000-00026.

Rugg, M. D. (1990). Event-related brain potentials dissociate repetition effects of high- and low-frequency words. *Memory & Cognition, 18*(4), 367–379. https://doi.org/10.3758/BF03197126.

Ruiz, J. R., Ortega, F. B., Castillo, R., Martín-Matillas, M., Kwak, L., Vicente-Rodríguez, G., ... Moreno, L. A. (2010). Physical activity, fitness, weight status, and cognitive performance in adolescents. *The Journal of Pediatrics, 157*(6), 917–922.e5. https://doi.org/10.1016/j.jpeds.2010.06.026.

Ruiz-Ariza, A., Grao-Cruces, A., de Loureiro, N. E. M., & Martínez-López, E. J. (2017). Influence of physical fitness on cognitive and academic performance in adolescents: A systematic review from 2005–2015. *International Review of Sport and Exercise Psychology, 10*(1), 108–133. https://doi.org/10.1080/1750984X.2016.1184699.

Sacchi, E., & Laszlo, S. (2016). An event-related potential study of the relationship between N170 lateralization and phonological awareness in developing readers. *Neuropsychologia, 91*, 415–425. https://doi.org/10.1016/j.neuropsychologia.2016.09.001.

Sassenhagen, J., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2014). The P600-as-P3 hypothesis revisited: Single-trial analyses reveal that the late EEG positivity following linguistically deviant material is reaction time aligned. *Brain and Language, 137*, 29–39. https://doi.org/10.1016/j.bandl.2014.07.010.

Scudder, M. R., Federmeier, K. D., Raine, L. B., Direito, A., Boyd, J. K., & Hillman, C. H. (2014). The association between aerobic fitness and language processing in children: Implications for academic achievement. *Brain and Cognition, 87*, 140–152.

Shvartz, E., & Reibold, R. C. (1990). Aerobic fitness norms for males and females aged 6 to 75 years: A review. *Aviation, Space, and Environmental Medicine, 61*, 3–11.

Stites, M. C., & Laszlo, S. (2017). Time will tell: A longitudinal investigation of brain-behavior relationships during reading development. *Psychophysiology, 54*(6), 798–808. https://doi.org/10.1111/psyp.12844.

Thomas, S., Reading, J., & Shephard, R. J. (1992). Revision of the physical activity readiness questionnaire (PAR-Q). *Canadian Journal of Sport Sciences, 17*, 338–345.

Vasold, K. L., Deere, S. J., & Pivarnik, J. M. (2019). Club and intramural sports participation and college student academic success. *Recreational Sports Journal, 43*(1), 55–66. https://doi.org/10.1177/1558866119840085.

Voss, M. W., Chaddock, L., Kim, J. S., VanPatter, M., Pontifex, M. B., Raine, L. B., ... Kramer, A. F. (2011). Aerobic fitness is associated with greater efficiency of the network underlying cognitive control in preadolescent children. *Neuroscience, 199*, 166–176. https://doi.org/10.1016/j.neuroscience.2011.10.009.

Weber-Fox, C., Davis, L. J., & Cuadrado, E. (2003). Event-related brain potential markers of high-language proficiency in adults. *Brain and Language, 85*(2), 231–244. https://doi.org/10.1016/S0093-934X(02)00587-4.

Welk, G. J., Jackson, A. W. J. R. M., Jr, Haskell, W. H., Meredith, M. D., & Cooper, K. H. (2010). The association of health-related fitness with indicators of academic performance in Texas schools. *Research Quarterly for Exercise and Sport, 81*(sup3), S16–S23. https://doi.org/10.1080/02701367.2010.10599690.

Wittberg, R. A., Northrup, K. L., & Cottrell, L. A. (2012). Children's aerobic fitness and academic achievement: A longitudinal examination of students during their fifth and seventh grade years. *American Journal of Public Health, 102*(12), 2303–2307. https://doi.org/10.2105/AJPH.2011.300515.

Woollams, A. M., Lambon Ralph, M. A., David, C., Plaut, & Patterson, K. (2007). SD-squared: On the association between semantic dementia and surface dyslexia. *Psychological Review; Washington, 114*(2), 316.