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SPECIAL ISSUE: FIFTY YEARS OF P300: WHERE ARE WE NOW?

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A systematic review of physical activity and cardiorespiratory fitness on P3b

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Abstract

Given accumulating evidence indicating that acute and chronic physical activity and cardio-respiratory fitness are related to modulation of the P3b-ERP component, this systematic review provides an overview of the field across the last 30+ years and discusses future directions as the field continues to develop. A systematic review was conducted on studies of physical activity and cardio-respiratory fitness on P3b. PubMed, Web of Science, and Scopus were searched from database inception to March 28, 2018. Search results were limited to peer-reviewed and English-written studies investigating typically developed individuals. Seventy-two studies were selected, with 39 studies examining cross-sectional relationships between chronic physical activity ($n = 19$) and cardio-respiratory fitness ($n = 20$) with P3b, with 16 and 17 studies reporting associations of P3b with physical activity and cardio-respiratory fitness, respectively. Eight studies investigated the effects of chronic physical activity interventions, and all found effects on P3b. Eight studies investigating P3b during acute bouts of physical activity showed inconsistent results. Nineteen of 23 studies demonstrated acute modulation of P3b following exercise cessation. Conclusions drawn from this systematic review suggest that physical activity and cardio-respiratory fitness are associated with P3b modulation during cognitive control and attention tasks. Acute and chronic physical activity interventions modulate the P3b component, suggesting short- and long-term functional adaptations occurring in the brain to support cognitive processes. These summary findings suggest physical activity and cardio-respiratory fitness are beneficial to brain function and that P3b may serve as a biomarker of covert attentional processes to better understand the relationship of physical activity and cognition.

KEYWORDS
acute exercise, attention, chronic exercise, ERP, executive function

1 | INTRODUCTION

The physical inactivity pandemic has emerged as a serious public health concern in the 21st century (Blair, 2009). Despite growing awareness of this issue, the prevalence of physical inactivity remains unchanged, as approximately 80% of adolescents and 25% of adults did not meet the physical activity guideline (Hallal et al., 2012; Sallis et al., 2016). Such a lifestyle has been found to exacerbate age-related cognitive decline, as physical inactivity has been associated with brain atrophy during older adulthood and an estimated 3.8%

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of dementia cases worldwide (Arnardottir et al., 2016; Sallis et al., 2016). Physical inactivity is further linked to deficits in cognitive development, given that physical activity is important to cognition and academic achievement during the school age years (Biddle & Asare, 2011; Donnelly et al., 2016).

To counteract the consequences of physical inactivity on cognitive and brain health, there has been a growing trend to promote physical activity (Heath et al., 2012). Related research stems from evidence of the beneficial association of physical activity and cardio-respiratory fitness with neurocognitive health, particularly higher-order cognitive processes such as cognitive control (also known as executive function) across the lifespan (Åberg et al., 2009; Donnelly et al., 2016; Etnier et al., 1997; Hillman, Erickson, & Hatfield, 2017; Hillman, Erickson, & Kramer, 2008; Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Sibley & Etnier, 2003). Further, meta-analyses and narrative reviews have indicated both acute and chronic effects of physical activity on cognitive control (Chang, Labban, Gapin, & Etnier, 2012; Colcombe & Kramer, 2003; Donnelly et al., 2016; Hillman et al., 2008, 2017; Ludyga, Gerber, Brand, Holsboer-Trachsler, & Pühse, 2016). Although the existing evidence overwhelmingly supports the benefits of physical activity on behavioral outcomes associated with cognition, the underlying mechanisms that give rise to this beneficial relationship have received less attention.

With the rapid growth of neuroimaging techniques in the 21st century, research has advanced our understanding of the neural underpinnings of physical activity-induced benefits to cognitive health (Voss, Vivar, Kramer, & van Praag, 2013). Derived from the neuroelectric system (EEG), ERPs have been one of the most prominent approaches to the study of physical activity and brain function (Hillman, Kamijo, & Pontifex, 2012). The high temporal resolution of ERPs affords the ability to investigate the influences of physical activity on cognitive processes that occur between stimulus engagement and response execution during tasks demanding a variety of cognitive operations (Fabiani, Gratton, & Coles, 2007).

Embedded within the stimulus-locked ERP, the P300 is a positive-going deflection occurring approximately 300 to 700 ms after stimulus presentation. The difference in voltage between this positive peak and a prestimulus baseline is defined as the amplitude of P300, while the time from stimulus onset to the component peak is referred to as P300 latency. Topographically and functionally dissociable from P3a, a subcomponent of P300 that is frontally centered and indicative of attentional orientating, P3b has a scalp distribution centered over parietal electrode sites and has been theorized to reflect the updating of a mental representation in working memory as the result of incoming stimuli (Donchin, 1981; Polich, 2007, 2012). Specifically, increases in P3b amplitude are thought to serve as an index of the attention-driven comparison process between a new event differing from that of the previous event that is maintained in working memory, with less probable events engendering larger P3b amplitude. Further, modulation of P3b amplitude is believed to represent the availability of attentional resources to implement cognitive processes related to task demands (Polich, 2007, 2012). P3b latency is thought to index processing speed related to stimulus classification and evaluation, suggesting its role in bridging perceptual and response processing (Verleger, Jaśkowski, & Wascher, 2005).

Individual differences in P3b latency have been associated with the lifespan trajectory of cognitive capacity, with research indicating decreasing latency across childhood development and increasing latency during adult aging (Polich, 2007, 2012). P3b latency is also sensitive to task demands related to stimulus encoding and response selection, with latency increasing when perceptual interference and response competition occur (Verleger et al., 2005). Taken together, previous research on the modulation of P3b amplitude and latency as a result of individual differences or experimental manipulations has led to the neuroinhibition hypothesis, which describes P3b as a neuroelectric consequence of the neural mechanism that inhibits extraneous brain activation to facilitate updating of mental representation from the memory system (Polich, 2007, 2012). Given that P3b has been associated with arousal levels regulated by locus coeruleus-norepinephrine (LC-NE) system (Murphy, Robertson, Balsters, & O'Connell, 2011; Nieuwenhuis, Aston-Jones, & Cohen, 2005), which is stimulated by physical activity (McMorris, Turner, Hale, & Sproule, 2016), P3b appears to be a candidate neuroelectric marker to study neuroinhibition underlying attentional processes during a variety of cognitive tasks in relation to physical activity and its physiological correlates (e.g., cardio-respiratory fitness).

Cross-sectional studies of P3b have indicated its association with physical activity and cardio-respiratory fitness. Physical activity refers to the bodily movement produced by skeletal muscles that results in energy expenditure (Caspersen, Powell, & Christenson, 1985). Related to physical activity, cardio-respiratory fitness is defined as the ability of the cardio-respiratory system to supply fuel during sustained physical activity and to eliminate fatigue product after supplying fuel (Caspersen et al., 1985). Although other aspects of fitness such as muscular (Firth et al., 2018; Kao, Westfall, Parks, Pontifex, & Hillman, 2017) and motor (Aadland et al., 2017; Voelcker-Rehage, Godde, & Staudinger, 2010) fitness have been associated with cognitive performance, limited evidence exists to determine their relationship with P3b. Regardless, research has shown that individuals with higher levels of physical activity or greater amounts of cardio-respiratory fitness exhibit larger P3b amplitude and shorter P3b latency, suggesting greater attentional resource allocation and faster processing speed in support of behavioral performance during cognitive operations (Hillman et al., 2012).

Such findings are further corroborated by studies, including randomized controlled trials, which have found larger P3b amplitude and shorter P3b latency following participation in acute (Hillman et al., 2012; Hillman, Kamijo, & Scudder, 2011) and chronic (Hillman et al., 2014; Hsieh, Lin, Chang, Huang, & Hung, 2017; Tsai, Pan, Chen, & Tseng, 2017) physical activity intervention. Accordingly, investigation of the P3b affords an understanding of the functional adaptations in the brain that occur during information processing and which may be amenable to physical activity intervention. This line of research is relevant as it may help to understand the potential of physical activity for improving cognition and brain health in individuals who exhibit altered P3b component underlying impaired cognitive performance (Kamijo et al., 2012; Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013; Song et al., 2016). As a result, research on the relation of physical activity and cardio-respiratory fitness to the P3b has been growing over recent decades (Figure 1). However, a systematic review summarizing the existing literature is currently absent. Thus, the purpose of the present study was to provide a comprehensive overview of the current state of research on the relation of acute and chronic physical activity and cardio-respiratory fitness with the P3b-ERP and provide recommendations to guide future research as the field continues to develop.

2 | METHOD

2.1 | Protocol and registration

Study procedures were based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA; Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009). This review was registered in the International Prospective Register of Systematic Reviews (CRD42017080871).

2.2 | Search procedure

Three electronic databases (PubMed, Web of Science, and Scopus) were selected for performing the search for publications occurring prior to March 28, 2018. When searching in PubMed, medical subject heading (MeSH) terms were utilized. The search terms physical activity, exercise intervention, sedentariness, and physical fitness were grouped using the connector “OR” and then were combined using the connector “AND” with search terms related to ERP parameters. The same selection strategy was used for Web of Science and Scopus without MeSH terms. Online supporting information, Table S1 presents the entire set of entry terms grouped by MeSH terms. As an example, a selected part of the PubMed search was: ("exercise"[MeSH] OR "sport"[MeSH]) OR "motor activity"[MeSH]) AND ("event-related potentials, P300"[MeSH] OR “late positive potential”). The complete search strategy used for each database is provided in supporting information, Appendix S1.

2.3 | Inclusion/exclusion criteria

Studies were eligible based on the following criteria: (a) Considered physical activity, exercise, sedentariness, and physical fitness as an independent variable. Investigations with a major focus on breathing and mental work (e.g., Tai-chi, mindfulness) or physical fitness measured by self-reported surveys were not included. (b) Considered measurements of P3b as a dependent variable. (c) Were written in English. (d) Focused on typically developed individuals (i.e., special populations such as elite athletes and participants with a diagnosed neuromotor disease were excluded). No age restriction was applied because the focus of our review was across the lifespan. Conference proceedings, systematics reviews, thesis/dissertations, unpublished studies, and non-peer-reviewed publications were excluded from this review.

2.4 | Risk of bias assessment

Two independent reviewers (C.C-S., S-C.K.) assessed the quality of the studies selected. Reviewers were trained previously for assessing the risk of bias of the studies selected. Initially, there

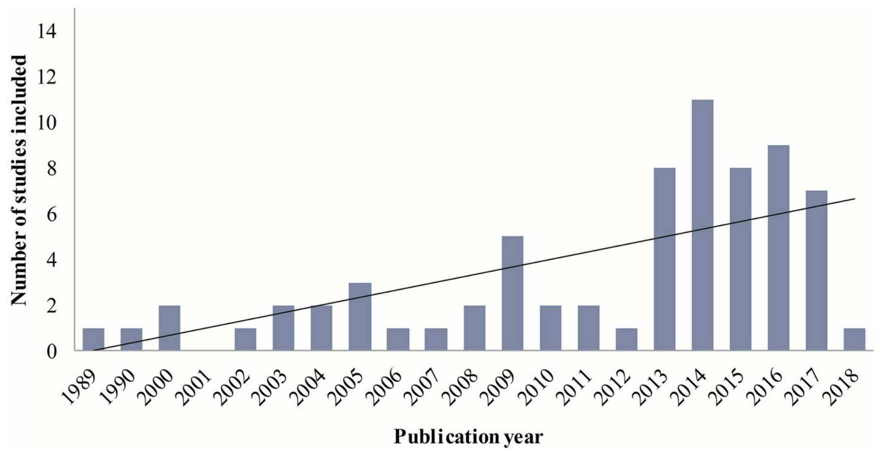

FIGURE 1 Number of studies included in this systematic review based on the publication year. Publication year of 2018 does not depict a complete year since the search performed occurred on March 28, 2018, covering only the first 3 months of the year

was strong agreement among reviewers allocating risk of bias scores (86.5%). Disagreements between reviewers were solved in a consensus meeting. The studies' methodological quality was assessed with an adapted scale based on Consolidated Standards of Reporting Trials (Moher, Schulz, & Altman, 2001) and the Studies in Epidemiology (von Elm et al., 2007) checklists as previously used by other authors (Smith et al., 2014). The criteria applied were (a) random selection of study sites or participants and the randomization procedure was adequately described; (b) adequate description of the study sample (i.e., number of participants, sex, and mean age); (c) adequate assessment/reporting of physical activity or exercise intervention, sedentary behavior, or fitness measurements (i.e., validity/reliability of tests reported and/or detailed description of testing protocols/intervention); (d) adequate assessment of the P3b component (i.e., measurement procedure and data reduction adequately described); and (e) adjustment for basic confounders in the statistical analyses when necessary (i.e., when associations between dependent variables and demographic variables were reported in studies using a nonrandomized experimental design; Table S2). Reviewers assigned 0 when the study did not meet a criterion and 1 when a criterion was met. Thus, a maximal score of 5 could be reached for each study. Studies that scored 0–2 were considered to have a high risk of bias, those that scored 3 were considered to have a moderate risk of bias, and those scoring 4–5 were categorized as low risk of bias (Figure 2, Table S3). Studies categorized as high risk of bias are included in the review, but their conclusions should be taken with caution.

2.5 | Study selection process

Two reviewers (C.C-S., S-C.K.) performed the study selection process of the found articles. First, titles and abstracts were examined to identify studies that met inclusion criteria. Second, the full text of eligible studies based on the screened studies was read to determine their final inclusion. Disagreements between reviewers were solved in a meeting between reviewers and an expert in the field (C.H.H.). Finally, articles including physical fitness, physical activity/exercise, and/or sedentary behavior as well as the P3b component were systematically reviewed. The flow diagram of the study selection process following PRISMA guidelines is shown in Figure 3.

2.6 | Data collection and extraction process

The final studies included were thoroughly examined, and the following data were extracted into the database: (a) first author's name and publication year (study reference); (b) sample size, age, sex, and related characteristics of the study sample; (c) physical activity, sedentary behavior, and/or physical fitness tests used; (d) P3b definition and

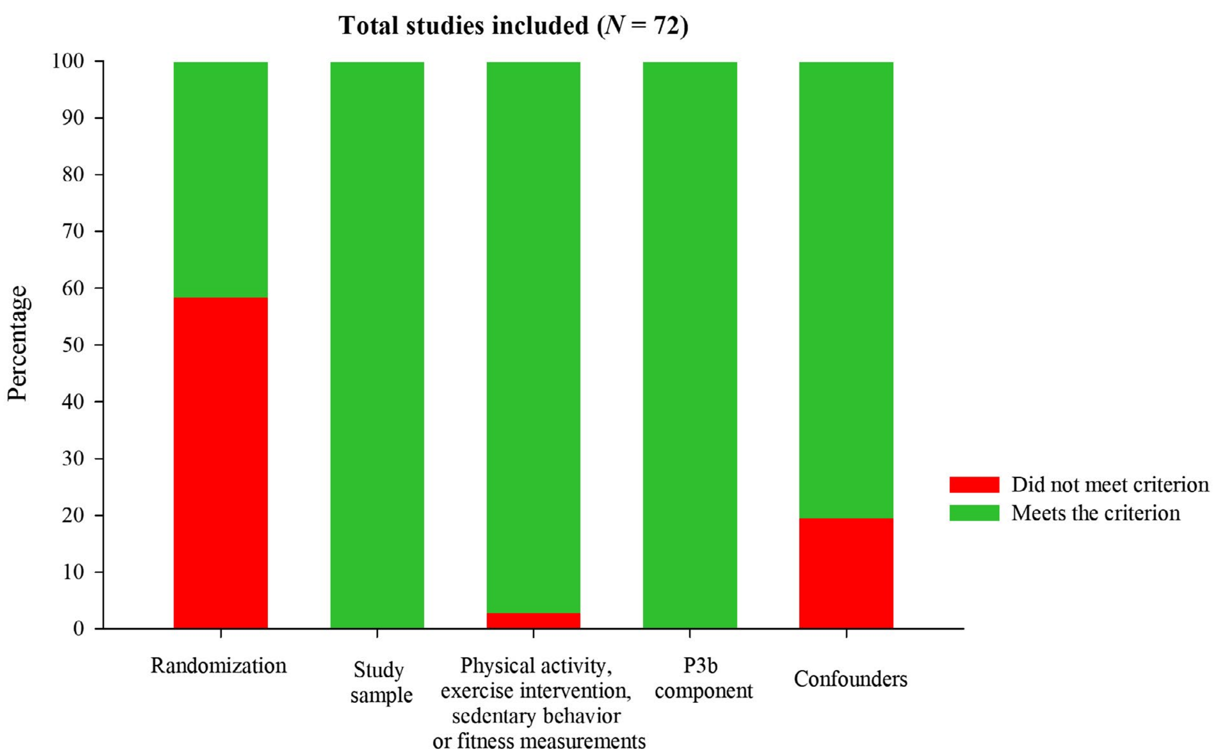

FIGURE 2 Risk of bias analysis for each criterion in the included studies ($n = 72$)

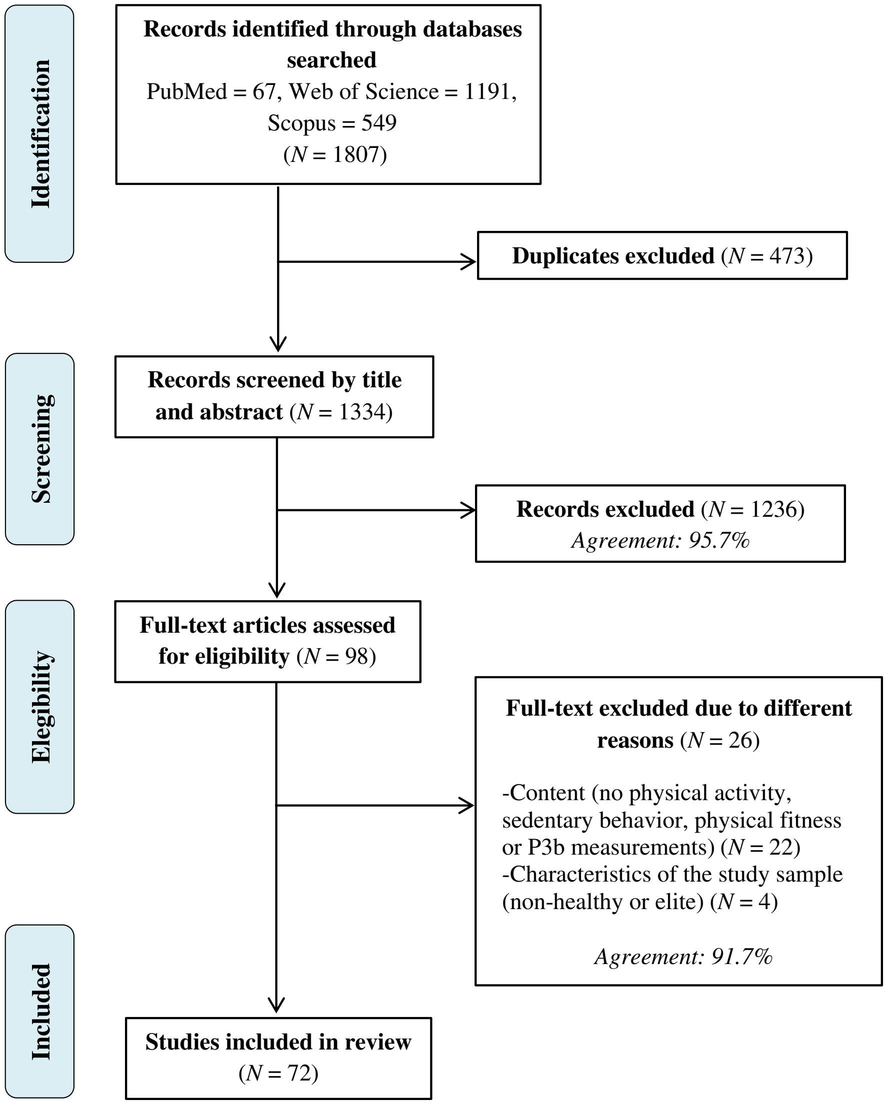

FIGURE 3 Flow diagram of studies included through the review process according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

task employed; and (e) the main outcomes. Additionally, for those studies with an intervention, detailed information about the intervention was extracted (i.e., type, duration, and intensity).

3 | RESULTS

3.1 | Study selection

A total of 1,807 studies were initially identified in PubMed, Web of Science, and Scopus. Of these, 473 were duplicated among databases and thus excluded in the first stage of the review. Therefore, a total of 1,334 studies were screened by title and abstract (first screening). After this first screening, 98 studies were further screened in full text (second screening), resulting in a total of 72 articles included in this review. The reasons for the full text exclusion are detailed in Figure 3. The agreement among reviewers in the first (95.7%) and second (91.7%) screenings was strong. See Tables 1–4 for a summary of study characteristics as well as the method for assessing physical activity, cardio-respiratory fitness, and P3b.

3.2 | Cross-sectional evidence of an association of physical activity with P3b

The findings in 16 of the 19 (84.2%) reviewed studies showed associations of physical activity with the P3b-ERP during performance on cognitive control and attention tasks (Chang et al., 2017; Chang, Huang, Chen, & Hung, 2013; Dai, Chang, Huang, & Hung, 2013; Fong, Chi, Li, & Chang, 2014; Gajewski & Falkenstein, 2015; Hatta et al., 2005; Hillman, Kramer, Belopolsky, & Smith, 2006; Huang, Lin, Hung, Chang, & Hung, 2014; Kamijo & Takeda, 2009, 2010; Tsai & Wang, 2015; Tsai, Wang, et al., 2016; Wang & Tsai, 2016), despite no effects in behavioral outcomes in three of the 19 (15.8%) studies (Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; McDowell, Kerick, Santa Maria, & Hatfield,

TABLE 1 Summary of the cross-sectional studies examining the association between physical activity, sedentary behavior, and physical fitness with the P3b component ($n = 40$)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Physical activity and sedentary behavior (N = 19)					
Berchicci et al. (2014)	• $N = 84$ (male = 57.1%, *19–86y*) • Young ($n = 30$; 24y) • Middle-aged ($n = 32$, 49y) • Older ($n = 22$, 73y)	• Self-report questionnaire for classifying participants between not exercise [≤ 6 METs] and exercise [> 6 METs]	• Peak amplitude and peak latency within a 250–700 ms post-stimulus window • Sites: Pz	• Visual simple response task • 5 blocks of 100 trials	• No physical activity-related differences in behavioral and P3b indices were found
Chang, Chu, et al. (2017)	• $N = 60$ (male = 63.3%, *55–70y*) • *Control* ($n = 20$, 57.5 ± 3.7y) • *Coordination* ($n = 20$, 59.2 ± 4.6y) • *Aerobic* ($n = 20$, 58.8 ± 3.8y)	• Self-report survey for classifying participation in aerobic or coordination (i.e., martial art, tai-chi) exercise ≥ 30 min 3 times per week. Control group did not regularly participate in exercise	• Mean amplitude within a 350–550 ms post-stimulus window • Sites: Fz, Cz, Pz	• Stroop task • 6 blocks of 60 trials (40 congruent and 20 incongruent)	• Both exercise groups exhibited reduced RT across congruency and higher ACC during incongruent condition than control group ($p \le 0.02$) • Higher ACC during the congruent than incongruent condition in the control and coordination but not the aerobic group • Aerobic group had larger P3b amplitude than coordination and control • Differences in P3b amplitude between congruent and incongruent conditions were only observed in the aerobic and coordination groups but not control group
Chang, Tsai, et al. (2013)	• $N = 40$ (male = 47.5%, *65–72y*) • *Low physical activity* ($n = 20$, 67.9 ± 2.1y) • *High physical activity* ($n = 20$, 67.9 ± 2.4y)	• IPAQ for classifying participants between: low physical activity level [< 600 METs/week] and high physical activity level [vigorous exercise > 1,500 METs/week or overall > 3,000 METs/week])	• Peak amplitude and latency within a 300–800 ms post-stimulus window • Sites: Fz, Cz, Pz	• Sternberg task • 4 blocks of 40 trials	• High physical activity group had shorter RT compared to those with lower physical activity ($p < 0.04$) • High physical activity group had larger P3b amplitude than low physical activity group • High physical activity group had shorter P3b latency than low physical activity group at Cz
Dai et al. (2013)	• $N = 48$ (male = 33.3%, *69.3 ± 3.7y*) • *Open skills* ($n = 16$, *69.0 ± 3.6y*) • *Closed skills* ($n = 16$, *69.9 ± 3.6y*) • *Irregular exercise* ($n = 16$, *67.3 ± 3.0y*)	• IPAQ for classifying participants in open- [table tennis or tennis], closed-skills [3 times per week, 30 min/session jogging and swimming], or irregular exercises [< 2 per week]	• Peak amplitude and latency within a 300–800 ms post-stimulus window • Sites: Fz, Cz, Pz	• Task-switching task • 1 block of 128 homogeneous trials and 1 block of 256 heterogeneous trials (128 non-switch, 128 switch trials)	• Both exercise groups had shorter RTs than the irregular exercise group • Both exercise groups exhibited larger P3b amplitude than the irregular exercise group across global and local switch conditions

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Fong et al. (2014)	• $N = 64$ (male = 50%, *20–75y*) • *Older adults endurance exercise* (OEE, $n = 16$, 68.*4 ± 3.7y*) • *Older adults Tai Chi Chuan* (OTC, $n = 16$, 67.*3 ± 4.9y*) • *Older adults sedentary lifestyle* (OSL, $n = 16$, 68.*9 ± 4.3y*) • *Young adults* (YA, $n = 16$, 22.*4 ± 2.6y*)	• Self-reported questionnaire (at least 5 years of exercise, three times a week, for 30 min each session) • IPAQ was included in the screening for verifying physical activity	• Peak amplitude and latency within a 300–550 ms post-stimulus window • Sites: Fz, Cz, Pz	• Task-switching task using S1–S2 (cue-target) paradigm • 2 blocks of 90 homogeneous trials and 3 blocks of 90 heterogeneous trials	• Shortest overall RT for YA, followed by OEE and OTC, and OSL. Only OSL exhibited lower ACC than YA during the heterogeneous condition • YA had lower switch cost compared to the other groups • OSL had smaller P3b amplitude than OEE, OTC, and YA at Cz and Pz • Only OEE had smaller P3b amplitude in the heterogeneous than homogeneous condition • OSL had a longer P3b latency than YA
Gajewski and Falkenstein (2015)	• $N = 40$ (male = 100%, *73.2 ± 4.5y*) • *Low active* ($n = 20$, 73.6 ± 4.9y) • *Physically active* ($n = 20$, 72.7 ± 4.3y)	• Self-reported questionnaire (physically active on average for 50 ± 13 years; range: 30–74 years) • Lüdenscheid activity questionnaire (an average of 290 min activity in 4.5 (1-hr) sessions per week in the current and past 2 years)	• Mean amplitude and peak latency within a 400–700 ms post-stimulus window • Site: Pz	• Task-switching task using S1–S2 (cue-target) paradigm with 3 rules • Each rule had 1 block of 34 homogeneous trials • 1 block of 126 heterogeneous trials with 33.3% switch trials	• Lower RT mixing costs and smaller RT variability for active than low active participants • Lower ACC mixing and switch costs for the active than low active group • Lower P3b amplitude in switch versus non- switch trials in the active group whereas the low active group exhibited no such differences
Getzmann et al. (2013)	• $N = 32$ (male = 100%, *63–88y*) • *Active* ($n = 16$, 73.0 ± 5.1y) • *Inactive* ($n = 16$, 73.2 ± 4.4y)	• Active group recruited from a local sports club and inactive group consisting of newcomers of a training study • Lüdenscheider activity questionnaire was used to confirm differences in physical activity between groups	• Peak amplitude and latency within a 225–400 ms and a 400–700 ms post-stimulus window for P3a and P3b, respectively • Site: FCz for P3a and Pz for P3b	• 3-stimulus auditory oddball task • 2 blocks of 120 trials (Target: Deviant:Nontarget = 1:1:8)	• The inactive group showed larger increases in RT due to deviant tones compared to active participants • No differences in P3b amplitude or latency were observed between inactive and active participants • Increased P3a amplitude was found in inactive compared to active participants
Hatta et al. (2005)	• $N = 40$ (male = 50%) • *Active* ($n = 20$, 69.2 ± 1.3y) • *Inactive* ($n = 20$, 66.9 ± 1.1y)	• Active group took part in exercise class > 3 years (rhythm, aerobic, strength, flexibility, and stretching at 60%–70% HR_{max}) • Inactive group consisted of newcomers to the class	• Peak amplitude and latency within a 250–500 ms post-stimulus window • Sites: Fz, Cz, Pz	• 2-stimulus somatosensory oddball task • 1 block of 150 trials (Target:Nontarget = 1:4)	• The active group showed shorter RT than the inactive group • The active group showed larger P3b amplitude than the inactive group • The active group showed larger P3b amplitude at Pz than Fz and Cz. The inactive group showed smaller P3b amplitude at Cz than Fz and Pz

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Hawkes et al. (2014)[†]	• *N* = 54 (male = 50%, *20–75y*) • *Tai-Chi* (*n* = 10, 55.4 ± 12.9y) • *Meditation & Exercise* (ME, *n* = 16, 48.6 ± 15.0y) • *Aerobic Exercise* (AE, *n* = 16, 44.1 ± 16.2y) • *Sedentary group* (SG, *n* = 12, 46.9 ± 12.8y)	• Self-reported questionnaire (the sedentary group was inactive for 5 years; the active groups practiced their chosen activity for 30-min sessions, 3 times per week for past 5 years)	• Peak amplitude and peak latency within a 0–500 ms post-stimulus window • Site: Pz	• Visuo-spatial task switching task • 4 blocks of 48 homogeneous trials and 12 blocks of heterogeneous 48 trials	• Tai Chi, ME, and AE groups showed shorter switch RTs than SG • Tai Chi and ME groups showed lower local percent switch costs than SG • Tai-Chi and ME showed larger P3b amplitude than GS but AE did not differ from SG
Hillman et al. (2004)	• *N* = 32 (male = 50%) • *High physically active older adults* (*n* = 8, 65.9 ± 8.1y) • *Moderate physically active older adult* (*n* = 8, 65.6 ± 6.3y) • *Low physically active older adult* (*n* = 8, 68.8 ± 5.3y) • *Younger adults control* (*n* = 8, 20.4 ± 1.9y)	• Self-reported physical activity history • Yale physical activity survey for older adults	• Peak amplitude and latency within a 250–600 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz.	• Modified flanker task • 5 blocks of 144 trials	• Young adults exhibited faster RT compared to all three older adult groups • Greater incompatible P3b amplitude at Fz for moderate and high active older adults compared to young adults. Decreased neutral amplitude at CPz for low active older adults compared to young adults • Young adults showed faster P3b latency than the low and moderate active older adults and not different from the high active older adults
Hillman et al. (2006)	• *N* = 66 (male = 51.5%) • *Active Older* (*n* = 17, 63.7 ± 0.9y) • *Active Younger* (*n* = 18, 19.4 ± 0.3y) • *Sedentary Older* (*n* = 15, 65.9 ± 0.8y) • *Sedentary Younger* (*n* = 16, 19.4 ± 0.2y)	• Yale physical activity survey for older adults (assessment of total hours of activity, kilocalorie expenditure, and the Yale Summary Index, which estimates the average amount of physical activity during the previous month)	• Peak amplitude and latency within a 275–750 ms post-stimulus window • Sites: Fz, F3/4, Cz, C3/4, Pz, P3/4	• Task-switching task • 1 block of 50 trials for each homogenous condition and 1 block of 256 heterogeneous trials	• Active participants showed shorter RT compared to sedentary participants • For global switch, physically active, compared to sedentary, participants had larger P3b amplitude at midline sites • For local switch, only physically active participants showed increased P3b amplitude at midline compared to lateral sites • Faster P3b latency for active relative to sedentary participants at the parietal region for the heterogeneous condition.

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Huang et al. (2014)	• $N = 60$ (male = 43.3%, *69.3 ± 3.7y*) • *Open skills* ($n = 20$, 69.4 ± 3.0y) • *Closed skills* ($n = 20$, 70.5 ± 2.6y) • *Irregular exercise* ($n = 20$, 68.3 ± 2.3y).	• Self-report questionnaires (participation in open- [table tennis, tennis and badminton] or closed- skills [jogging and swimming] for 30-min sessions, 3 times per week > 3 months) • IPAQ (classifying inactivity [< 600 METs min/week], low activity [600–3000 METs min/week] and sufficient activity [> 3,000 METs min/week])	• Peak amplitude and latency within a 300–700 ms post-stimulus window • Sites: Fz, Cz, Pz	• Modified flanker task • 5 blocks of 44 trials	• Regular exercisers exhibited faster RT compared to irregular exercisers • For the P3b amplitude of the open-skill exerciser group, the peak amplitude was larger at the vertex site compared to the frontal site, whereas no site differences were observed in the closed-skill and irregular exerciser groups • No significant differences were observed between groups in P3b latency
Kamijo et al. (2009)	• $N = 40$ (male = 52.5%, *21.1 ± 0.3y*) • *Active group* (AG, $n = 20$) • *Sedentary* group (SG, $n = 20$)	• IPAQ (total physical activity score [kcal/week], leisure-time domain sub-score [kcal/week], and vigorous-intensity sub-score [kcal/week]	• Peak amplitude and latency of within a 250–500 ms post-stimulus window • Sites: Fz, Cz, Pz	• Spatial priming task • 3 blocks of 72 trials (54 trials for positive priming, 54 trials for negative priming, and 108 trials for control)	• Shorter RTs in the positive priming than control condition for SG but not AG • AG had shorter P3b latency than SG in positive and negative priming conditions • The increases in P3b latency from the negative priming to control condition were larger for AG than SG • AG showed larger P3b amplitude at Cz and Pz compared to Fz for positive priming and control conditions while no such effects were observed for SG
Kamijo and Takeda (2010)	• $N = 40$ (male = 52.5%, *21.4 ± 0.3y*) • *Active group* (AG, $n = 20$, 20.4 ± 0.3y) • *Sedentary* group (SG, $n = 20$, 22.3 ± 0.4y)	• IPAQ (total physical activity score [kcal/week], leisure-time domain sub-score [kcal/week], and vigorous-intensity sub-score [kcal/week]	• Peak amplitude and latency within a 250–600 ms post-stimulus window • Sites: Fz, Cz, Pz for amplitude; Pz for latency	• Modified task-switching task • 1 block of 64 trials for each homogeneous condition and 4 blocks of 64 heterogeneous trials	• Smaller mixing and switch cost on RT for AG relative to SG • Smaller mixing cost on P3b amplitude for AG relative to SG while no significant differences were observed for P3b latency
McDowell et al. (2003)	• $N = 73$ (male = 45.2%) • *High active young adults* ($n = 21$, 22.3 ± 0.9y) • *Low active young adults* ($n = 16$, 23.1 ± 0.8y) • *High active older adults* ($n = 18$, 66.1 ± 0.8y) • *Low active older adults* ($n = 18$, 69.3 ± 0.8y)	• Modified physical activity questionnaire (high active group engaged in regular physical activity at a sufficiently high intensity and duration; low active group engaged in irregular activity confined to low intensity)	• Peak amplitude, mean amplitude (200 ms around the peak), and peak latency within a 300–600m post-stimulus window • Sites: Fz, Cz, C3/4, Pz, T3/4, O1/2	• 2-stimulus visual oddball task • 1 block of 120 trials (Target:Nontarget = 1:4)	• Low active older adults exhibited greater P3b mean amplitude across all sites than all three other groups • Larger P3b peak amplitude at Fz was observed for low active older adults than all three other groups • High active younger adults showed higher P3b amplitude than low active younger adults at Pz, C3, C4, O1, and O2, while this pattern was reversed in older adults

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Polich and Lardon (1997)	• $N = 22$ (male = 72.7%, *30–34.7y*) • *Low exercise* ($n = 11$) • *High exercise* ($n = 11$)	• *Low exercise*: < 5 hr per week and minimal aerobic activity without previous participation in high-level sports • *Higher exercise:*> 5 hr per week participation in sports or > 3 years of vigorous aerobic exercise	• Peak amplitude and latency within a 250–500 ms post-stimulus window after the N100-P200-N200 complex. • Sites: Fz, Cz, Pz	• 2-stimulus auditory and visual oddball tasks (Target:Nontarget = 1:4) • At least 30 artifact-free target trials were obtained for each stimulus modality	• Task performance did not differ across groups or experimental conditions • Low exercise participants demonstrated smaller P3b amplitude than high-exercise subjects ($F_{(1,20)} = 4.5$, $p < 0.05$) • Larger increases in P3b latency between visual and auditory tasks for the low exercise compared to the high-exercise group
Tsai, Wang, et al. (2016)	• $N = 60$ (male = 66.7%, *60–80y*) • *Open-Skill* ($n = 20$, 65.3 ± 4.1y) • *Close-Skill* ($n = 20$, 66.9 ± 4.7y) • *Control* ($n = 20$, 64.3 ± 3.6y)	• Self-report exercise for 30-min bouts at least 3 times per week in the last 2 years (open-skill: table-tennis or badminton; close-skill: swimming or jogging; control: < 30-min of exercise < 2 times per week in last 2 years)	• Mean amplitude within a 280–600 ms post-stimulus window • Sites: Fz, Cz, Pz	• Visuospatial attention task (modified central cue Posner task) • 3 blocks of 90 trials (54 trials in valid cue condition, 27 trials in invalid cue condition, 9 trials in neutral condition)	• Both groups exhibited reduction in overall RTs compared to the control group, and the Open-Skill showed faster RT compared to the Closed-Skill group • Open-Skill (6.45μV) and Close-Skill (5.09μV) exhibited larger target-elicited P3b amplitude than control (2.99μV) • Open-Skill exhibited marginally larger P3b amplitude than Close-Skill ($p = 0.052$)
Tsai and Wang (2015)	• $N = 64$ (male = 64.1%, *60–77y*) • *Open-Skill* ($n = 21$, 65.4 ± 4.2y) • *Close-Skill* ($n = 22$, 66.0 ± 4.1y) • *Control* ($n = 21$, 63.9 ± 3.4y)	• Self-report exercise for 30-min exercise at least 3 times per week in the last 2 years (open-skill: table-tennis or badminton; close-skill: swimming or jogging; control: < 30-min of exercise < 2 times per week in last 2 years)	• Mean amplitude and peak latency within a 350–600 ms post-stimulus window • Sites: Fz, Cz, Pz	• Task switching (odd-even/greater-less than 5 decision) • 4 blocks of 56 homogeneous trials and 4 blocks of 112 heterogeneous trials	• Two exercise groups exhibited shorter RT compared to the control group • Open-Skill exhibited faster RT in the switch condition and a smaller switch-cost compared to the closed-skill and control groups • Open-Skill and Close-Skill showed larger P3b amplitude than the control group • Open-Skill showed larger P3b amplitude than Close-Skill and the control group in the switch condition
Wang et al. (2016)	• $N = 48$ (male = 75%) • *Active older adults* ($n = 24$, 66.6 ± 14.3y) • *Sedentary older adults* ($n = 24$, 67.3 ± 1.2y)	• Self-reported 7-day recall questionnaire (active group exercised at moderate intensity or higher 5 hr/week; sedentary group spent less than 2 hr/week exercising at moderate intensity or higher)	• Peak amplitude and peak latency within a 300–600 ms post-stimulus window • Sites: Fz, Pz	• Non-delayed and Delayed matching-to-sample task • 3 blocks of 72 trials non-delayed and delayed conditions	• The active group had higher ACC compared to sedentary group • The active group showed larger P3b amplitude than the sedentary group • Physical activity was positively associated with ACC in both delayed and non-delayed conditions as well as with P3b amplitude at Fz in the delayed condition

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Physical fitness (N = 21)					
Dustman et al. (1990)	• *N* = 60 (male = 100%, *20–62y*) • *High fit young* (*n* = 15, 24.1 ± 2.9y) • *High fit old* (*n* = 15, 53.8 ± 3.0y) • *Low fit young* (*n* = 15, 26.3 ± 2.6y) • *Low fit old* (*n* = 15, 55.9 ± 3.2y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Peak latency around a 400 ms post-stimulus window • Sites: Fz, Cz, Pz for amplitude and Cz and Pz for latency	• 2-stimulus visual oddball task • 1 block of 200 trials (Target:Nontarget = 4:21)	• Low fit old group exhibited longer P3b latency than high fit old group, $t(28) = 2.11$, $p < 0.05$
Emmerson et al. (1989)	• *N* = 60 (male = 100%, *40.1 ± 15.3y*) • *Higher fit* (*n* = 30, 39.3 ± 15.3y) • *Lower fit* (*n* = 30, 41.1 ± 15.3y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a maximal exercise test on a motor driven treadmill)	• Peak latency within a 300–600 ms post-stimulus window • Sites: Fz, Cz, Pz	• 2-stimulus visual oddball task • 1 block of 200 trials (Target: Nontarget = 4:21)	• Increased age was associated with longer P3b latency for the lower fit group ($p < 0.001$) but such age-related increases were not observed for the higher fit group ($p > 0.10$)
Hawkes et al. (2014)[†]	• *N* = 54 (male = 50%, *20–75y*)	• *Cardiorespiratory fitness* (VO_{2max} estimated by Rockport 1-mile walk)	• Peak amplitude and latency within a 0–500 ms post-stimulus window • Site: Pz	• Visuo-spatial task switching task • 4 blocks of 48 homogeneous trials and 12 blocks of heterogeneous 48 trials	• VO_{2max} was related negatively with switch RT ($r = -0.508$, $p < 0.001$) • VO_{2max} was positively related with switch P3b amplitude ($r = 0.324$, $p < 0.0125$) • Shorter switch RT was correlated with larger P3b switch amplitude
Higuchi et al. (2000)	• *N* = 9 (male = 100%, *29.7 ± 8.1 y*)	• *Muscular strength* (handgrip test)	• Peak amplitude and latency within a 0–500 ms post-stimulus window • Sites: Fz, Cz, Pz.	• 2-stimulus auditory oddball task • 1 block of 150 trials (Target:Nontarget = 1:4)	• P3b amplitude and latency were not associated with grip strength measured in right and left hands (*rs* < −0.284) • P3b amplitude and latency were not correlated with RT
Hillman et al. (2005)	• *N* = 51 (male = 51%) • *Higher fit* children (*n* = 12, 9.3 ± 1.2y) • *Higher fit* adults (*n* = 15, 19.1 ± 1.2y) • *Lower fit* children (*n* = 12, 9.8 ± 0.6y) • *Lower fit* adults (*n* = 12, 19.5 ± 1.5y)	• *Cardiorespiratory fitness* (assessed by PACER)	• Peak amplitude and latency within a 275–775 ms post-stimulus after the N1, P2, N2 complex. • Sites: Fz, Cz, Pz, Oz.	• 2-stimulus visual oddball task • 3 blocks of 150 trials (Target:Nontarget = 1:4)	• Higher fit children had shorter RT compared with lower fit children • Higher fit children exhibited larger P3b amplitude than the other three groups ($t_{(1,22)} \geq 3.7$, $p < 0.001$) • Faster P3b latency at Oz for higher fit compared with lower fit participants ($F_{(1,49)} = 4.6$, $p < 0.05$)

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Hillman et al. (2009)	• $N = 38$ (male = 52.6%) • *Higher fit* ($n = 19$, 9.3 ± 0.9 y) • *Lower fit* ($n = 19$, 9.5 ± 1.0 y)	• *Cardiorespiratory fitness* (assessed by PACER)	• Peak amplitude, mean amplitude, and peak latency within a 375–675 ms post-stimulus window • Sites: Fz, F3/4, F7/8, Cz, C3,/4, C7/8, Pz, P3/4, P7/8	• Modified flanker task • 6 blocks of 52 trials	• Higher fit participants exhibited greater ACC than lower fit participants but significant differences were not observed between groups in RTs • Higher fit participants exhibited larger P3b peak and mean amplitude over central and parietal regions compared to lower fit participants • No effects of fitness were observed in P3b latency
Hillman et al. (2002)	• $N = 48$ (male = 50%, *18–70y*) • *Older-Fit* ($n = 12$, 63.5 ± 2.8y) • *Older-Sedentary* ($n = 12$, 65.0 ± 2.7y) • *Younger-Fit* ($n = 12$, 22.1 ± 3.3y) • *Younger-Sedentary* ($n = 12$, 23.3 ± 3.3y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a graded exercise test on a treadmill)	• Peak amplitude and peak latency within a 250–600 ms window following N1-P2-N2 complex after S1 and S2 • Sites: Fz, F3/4, Cz, C3/4, Pz, P3/4	• S1–S2-S3 visual discrimination task • S1 = warning signal; S2 = decision signal; S3 = response signal • 3 blocks of 48 trials	• No significant differences in RT between groups • Older sedentary adults showed longer P3b latency than older fit adults, ($F = 5.6$, $p < 0.025$) at lateral sites
Kamijo and Masaki (2016)	• $N = 38$ (male = 52.6%) • *Higher fit* ($n = 19$, 10.6 ± 0.8y) • *Lower fit* ($n = 19$, 10.7 ± 1.2y)	• *Cardiorespiratory fitness* (assessed by PACER)	• Mean amplitude and peak latency of within 600–1,100 ms post-cue and 400–700 ms post-probe windows • Sites: CPz (cue-P3) and Pz (probe-P3)	• Child-friendly AX-CPT task • Pressed a button with the right index finger when the target probe was preceded by the target cue (AX); Non-target trials, which required a button press with the right middle finger, consisted of three types: AY, BX, and BY trial • 4 blocks of 100 trials (AX:AY:BX:BY = 16:3:3:3)	• Higher fit children exhibited greater ACC for BX relative to AY trials, whereas lower fit children had comparable response accuracies for AY and BX trials • Larger cue-P3b amplitudes for the BX relative to the AY trials for the higher fit group while no such difference was observed for the lower fit group • No significant differences were observed between groups in P3b-probe amplitude
Luque-Casado et al. (2016)	• $N = 42$ (male = 100%) • *Higher fit* ($n = 22$, 21–24y) • *Lower fit* ($n = 20$, 22–24y)	• *Cardiorespiratory fitness* (VO_{2peak} at ventilatory anaerobic threshold assessed by an incremental effort test on a cycle ergometer)	• Mean amplitude within a 240–440 ms post-stimulus window • Sites: Pz, POz	• 60-min Psychomotor vigilance task	• Shorter RT in higher fit than in lower fit participants in the first 36 min of the task • Higher fit group showed greater P3b amplitude than the lower fit group in all blocks ($ps \leq 0.0001$)

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Magnie et al. (2000)*	• $N = 20$ (male = 100%, *18–30y*) • *Cyclists* ($n = 10$, 21.2y) • *Sedentary* ($n = 10$, 22.9y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a continuous incremental test on a cycle ergometer)	• Peak amplitude and latency within a 250–400 ms post-stimulus window • Sites: Fz, Cz, Pz,	• 2-stimulus auditory oddball (Target:Nontarget = 1:4) • 2 blocks containing at least 20 artifact-free target trials	• No significant association of fitness with task performance and P3b was observed
Moore et al. (2013)	• $N = 93$ (male = 58.1%, *8.8 ± 0.6y*)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Peak amplitude and latency within a 400–700 ms post-stimulus window • SDs of P3 amplitude and latency were measured using single trial analysis • Site: Pz	• Modified flanker task • 2 blocks of 75 trials	• Higher fitness was associated with shorter and less variable RT only for the incompatible condition • Longer mean P3b latency was associated with higher fitness
Moore et al. (2014)	• $N = 40$ (male = 60%, *9–10y*) • *Higher fit* ($n = 20$, 9.9 ± 0.7y) • *Lower fit* ($n = 20$, 10.1 ± 0.6y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Mean amplitude (50 ms surrounding the peak) and peak latency within a 300–600 ms post-stimulus window • Sites: left (P7, PO7, P5, PO5, P3, PO3), center (P1, PZ, OZ, P2), right (P8, PO8, P6, PO6, P4, PO4)	• Arithmetic verification task (a + b = c) • 120 trials using single-digit between 1 and 4 (60 correct, 60 incorrect) • 120 trials using single-digit between 6 and 9 (60 correct, 60 incorrect)	• Higher fit children showed higher *d'* than lower fit children during large size problems • Higher fit children had smaller P3b amplitude relative to lower fit during small problems
Pontifex et al. (2009)	• $N = 48$ (male = 60.4%, *18–73y*) • *Higher fit younger adults* ($n = 12$, 20.3 ± 1.1y) • *Lower fit younger adults* ($n = 13$, 20.1 ± 1.5y) • *Higher fit older adults* ($n = 10$, 66.2 ± 3.5y) • *Lowe fit older adults* ($n = 13$, 67.4 ± 3.2y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Peak amplitude and latency of P3a and P3b within a 300–700 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz, Oz	• 2-stimulus visual oddball task (Target:Nontarget = 1:4) • 3-stimulus visual oddball task (Target:Distraction:Nontarget = 12:12:76) • 3 blocks of 200 trials for each task	• During the 2-stimulus oddball task, higher fit individuals yielded shorter RT and increased P3b amplitude compared to their lower fit age-matched counterparts • During the 3-stimulus oddball, larger P3b amplitude, but not in P3a, was observed higher fit than lower fit only in younger adults

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Pontifex et al. (2011)	• $N = 48$ (male = 52.1%) • *Higher fit* ($n = 24$, 10.0 ± 0.6y) • *Lower fit* ($n = 24$, 10.1 ± 0.6y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Peak amplitude and latency within a 350–600 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz, Oz	• Modified flanker task • 2 blocks of 100 trials for each response-stimulus mapping (compatible and incompatible) conditions	• Lower fit children showed decreased ACC from the compatible to incompatible task condition but higher fit showed maintained ACC across task conditions • Higher fit children showed larger P3b amplitude than lower fit children • Higher fit children larger P3b amplitude for the compatible than incompatible condition but lower fit children did not show such P3b upregulation • Longer P3b latency for lower fit than higher fit children at the central, centro-parietal, parietal, and parieto-occipital sites
Scisco et al. (2008)	• $N = 52$ (male = 36.5%, *19.6 ± 1.6y*) • *Higher fit* ($n = 26$) • *Lower fit* ($n = 26$)	• *Cardiorespiratory fitness* (VO_{2max} estimated by submaximal exercise using the YMCA protocol on a cycle ergometer)	• P3 peak amplitude and latency within three different post-stimulus windows (300–450, 475–525, 250–750 ms) • Sites: Fz, F3/4, F7/8, FCz, FC3/4, FT7/8, Cz, C3/4, T7/8, CPz, CP3/4, TP7/8, Pz, P3/4, P7/8	• Task-switching task • 1 block of 51 homogeneous trials for each of 4 conditions for a total of 204 trials; 1 block of 50 heterogeneous trials for a total of 200 trials with each condition randomly presented	• No significant differences were found in RT or ACC • No significant differences were found between higher fit and lower fit in P3b analyses of peak amplitude or latency
Song et al. (2016)	• $N = 100$ (male = 100%, *18–25y*) • *Normal-weight and high-fit* (NH, $n = 25$, 21.0 ± 1.8y) • *Obese-weight and high-fit* (OH, $n = 25$, 20.8 ± 2.3y) • *Normal-weight and low-fit* (NL, $n = 25$, 22.0 ± 2.2y) • *Obese-weight and low-fit* (OL, $n = 25$, 21.2 ± 2.2y)	• *Cardiorespiratory fitness* (VO_{2max} estimated by submaximal exercise using the YMCA protocol on a cycle ergometer)	• Peak amplitude and latency of within a 300–700 ms post-stimulus • Sites: Fz, Cz, Pz	• Stroop task • 6 blocks of 72 trials	• NH exhibited shorter RT during the neutral condition compared to NL and OL • OL exhibited longer RT during the incongruent condition compared to other three groups • Larger P3b amplitude for NH compared to NL, OH, and OL • NH and NL exhibited larger P3b amplitude for the incongruent condition than the neutral condition while no such condition effect was observed for OH and OL

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Stroth et al. (2009)[*]	• $N = 33$ (male = 60.6%, *14.2 ± 0.5y*) • *Higher fit* ($n = 17$, 14.2 ± 0.4y) • *Lower fit* ($n = 16$, 14.3 ± 0.6y)	• *Cardiorespiratory fitness* (maximal watt performance assessed by a dynamometer while paddling using a graded exercise protocol)	• Peak amplitude and latency within a 340–440 ms post-stimulus window • Sites: C3, C4	• Go/nogo - Flanker task • 5 blocks of 120 trials (300 go-trials and 300 nogo-trials) • Feedback provided after each trial and reward was provided for high ACC	• No significant differences in task performance were observed between higher and lower fit participants • No differences in P3b amplitude or latency between groups ($ps > 0.76$)
Tsai, Wang, et al. (2014)[*]	• $N = 40$ (male = 100%) • *Higher-fit* ($n = 20$, 22.2 ± 2.2y) • *Lower-fit* ($n = 20$, 23.1 ± 2.2y)	• *Cardiorespiratory fitness* (VO_{2max} assessed using a modified Bruce protocol on a treadmill)	• Peak amplitude and latency within a 300–700 ms post-stimulus window • Site: Cz, Pz	• Modified visuospatial attention task • 3 blocks of 90 trials (54 trials in the valid cue condition, 27 trials in the invalid cue condition, 9 trials in the neutral condition)	• The higher fit group showed faster overall RT than the lower fit group • The higher fit group (9.72μV) showed larger P3b amplitude than the lower fit group (6.61μV)
Tsai, Wang, et al. (2016)[*]	• $N = 40$ (male = 100%) • *Higher fit* ($n = 20$, 22.2 ± 2.2y) • *Lower fit* ($n = 20$, 22.7 ± 1.9y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a graded maximal exercise test)	• Peak amplitude within a 250–600 ms post-stimulus window • Site: Pz	• Task-switching task • 1 block of 64 trials for each homogeneous condition and 4 heterogeneous blocks of 64 trials	• The higher fit group exhibited shorter RT in the switch and non-switch conditions as well as smaller inverse efficiency in non-switch condition compared to the lower fit group • The higher fit group showed larger P3b amplitude in pure and switch conditions compared to the lower fit group
Wang et al. (2016)	• $N = 48$ (male = 100%, *22.5 ± 2.2y*)	• *Cardiorespiratory fitness* (VO_{2max} assessed using a modified Bruce protocol on a treadmill)	• Peak amplitude and latency within a 200–400 ms post-stimulus window • Site: Pz	• Modified visuospatial attention task • 3 blocks of 90 trials (54 trials in the valid cue condition, 27 trials in the invalid cue condition, 9 trials in the neutral condition)	• Higher cardiorespiratory fitness was associated with shorter RT in the valid condition • Higher cardiorespiratory fitness was associated with larger P3b amplitude and shorter P3b latency in the valid condition and larger P3b amplitude in the invalid condition • P3b amplitude was a full mediator of the relationship between cardiorespiratory fitness and RT in the valid condition

(Continues)

TABLE 1 (Continued)

Study reference	Characteristics of the study sample	Physical activity, sedentary behavior, and/or physical fitness (tests)	P3b component: Definition	P3b component: Task	Main findings
Wu and Hillman (2013)	• $N = 39$ (male = 46.2%) • *Higher Fit* ($n = 19$, 10.1 ± 0.4y) • *Lower Fit* ($n = 20$, 10.1 ± 0.5y)	• *Cardiorespiratory fitness* (VO_{2max} assessed by a modified Balke protocol on a motor-driven treadmill)	• Peak amplitude and latency within a 350–650 ms post-stimulus window for Lag 4 T1-elicited trials • Peak amplitude and latency within a 900–1,100 ms post-stimulus window for Lag 4 T2-elicited trials • Peak amplitude and latency within a 1,200–1,400 ms post-stimulus window for Lag 8 T2-elicited trials • Sites: Fz, FCz, Cz, CPz, Pz	• Attentional blink task: Each single target trial (T1) presented 15 or 19 stimuli consisting of a random digit from 2–9 (T1) and a blank screen, interspersed within a stream of letters. Dual target trials were presented similarly but the blank screen was replaced with a random digit (T2). The distances from T1 to blank or T2 were short (Lag 4) or long (Lag8). At the end of each trial, participants reported numbers presented during the stimulus sequence and whether T2 was presented. • 4 blocks of 102 trials in total, with 192 T2-Lag4 trials, 72 T2-Lag8 trials, 72 T1-Lag4 trials, and 72 T1-Lag8 trials	• Higher fit children were associated with greater T2 ACC compared to lower fit children • Larger T1-elicited P3b amplitude for lower fit children (7.8 ± 0.6μV) compared to higher fit children (5.3 ± 0.6μV) • Larger T2-elicited P3b amplitude for lower fit (15.7 ± 1.5μV) compared to higher fit children (10.7 ± 1.5μV)

Note: Abbreviations: ACC, response accuracy; HR_{max}, maximum heart rate; IPAQ, International Physical Activity Questionnaire; MET, metabolic equivalent; RT, response time; VO_{2max}, maximum oxygen consumption (ml/kg/min); VO_{2peak}, peak oxygen consumption (ml/kg/min).

*Studies also investing the acute effects of physical activity on P3b.

†Studies reporting both the associations of physical activity and fitness with P3b.

TABLE 2 Summary of the experimental studies examining the chronic effect of physical activity intervention on the P3b component ($n = 8$)

Study reference (design)	Characteristics of the study sample	Physical fitness	Physical activity/control program: Type	Duration	Intensity	P3b component: Definition	Task	Main findings
Cetin et al. (2010) (RCT)	• *Control* ($n = 12$, male = 10, 71 ± 9.1y) • *Exercise* ($n = 11$, male = 9, 69.6 ± 8.6y) • *Vitamin E* ($n = 10$, male = 8, 73.1 ± 4.5y) • *Exercise & Vitamin E* ($n = 10$, male = 7, 72.8 ± 7.1y)	• Not applicable	• Aerobic walking	• 3 sessions per week for 6 months	• Exercise: In the first 2 weeks, exercise at 60%–70% HRR for 20 min/day, with a 5-min/day increase until week 8, then maintained at 50-min/day until the end of the study	• Peak to peak amplitude and latency between N2 and P3b • Sites: Fz, Cz	• 2-stimulus auditory oddball task (Target:Nontarget = 1:4) • The number of trials was not reported	• Exercise and Exercise & Vitamin E groups showed decreases in P3b latency at Fz and from pre- to post-test
Chang, Tsai, et al. (2013) (RCT)	• $N = 26$ (male = 50%, • *7.1 ± 0.33y*) • Low-intensity (LI, $n = 13$, 7.2 ± 0.3y, BMI = 16.7 ± 2.0) • Moderate-intensity (MI, $n = 13$, 7.0 ± 0.3y, BMI = 17.3 ± 1.5)	• Power (standing long jump) • Muscular endurance (1-min curl-up) • Flexibility (sit-and-reach) • Balance (one leg standing with eyes closed)	• Soccer activities	• 2 sessions of 35-min per week for 8 weeks	• *Low-intensity*: HR = 103.7 ± 8.3 • *Moderate-intensity*: HR = 140.2 ± 9.5	• Peak amplitude and latency within a 300−800 ms post-stimulus window • Sites: Fz, Cz, Pz	• Modified flanker task • 4 blocks of 52 trials	• MI group improved muscular endurance and flexibility. Both groups decreased BMI • Both groups improved overall ACC and RT from pre- to post-test, with larger improvements for incongruent trials • Both groups increased P3b amplitude and reduced P3b latency at post-test compared to pre-test
Chuang et al. (2015) (NRT)	• $N = 26$ (male = 0%) • *Dance revolution group* (DDRG, $n = 7$, 69.43 ± 3.82y) • *Brisk walking group* (BWG, $n = 11$, 67.01 ± 1.67y) • *Control group* ($n = 8$, 68.25 ± 3.96y)	• *Cardiorespiratory fitness* (VO_{2max} estimated by a submaximal exercise using the YMCA protocol on a cycle ergometer)	• *DDRG*: Dance exergame • *BWG:* Aerobic walking • *Control group:* maintained a sedentary lifestyle	• DDRG and BWG: 30-min sessions, 3 times each week for 12 weeks	• DDRG and BWG: 40%–60% of HR_{max} with a goal of maintaining 50% of HR_{max}	• Peak amplitude and latency within a 375−675 ms post-stimulus window • Site: Pz	• Modified flanker task • 5 blocks of 44 trials	• DDRG showed greater improvements in VO_{2max} than the control group • DDRG and BWG showed improved RT while the control group showed increased RT at post- compared to pre-test • DDRG and BWG showed shorter P3b latency at post-test than the control group
Hillman et al. (2014) (RCT)	• $N = 223$ (male = 54.3%) • *Exercise group* (EG, $n = 109$, 8.8 ± 0.1y, BMI = 19.1) • *Wait-list group* (WG, $n = 112$, 8.8 ± 0.1y, BMI = 18.9)	• *Cardiorespiratory fitness* (VO_{2peak} assessed by a modified Balke protocol on a motor-driven treadmill)	• *EG:* afterschool program targeting improvements in cardiorespiratory fitness and motor skills • *WG*: routine daily activities	• 2 hr per day (> 70-min) for 150 days of the 170-day school year • Attended 80.6 ± 15.1% of the scheduled sessions	• Moderate-to-vigorous physical activity (HR = 137 ± 8.3)	• Mean amplitude (50 ms around peak) and peak latency within a 300−700 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz, Oz	• Modified flanker task: 2 blocks of 75 trials • Task-switching task: 2 blocks of 60 homogeneous trials and 3 blocks of 50 heterogeneous trials	• EG showed larger increases in VO_{2max} and smaller increases in BMI compared to WG • EG showed larger increases in overall ACC and incongruent P3b amplitude, and greater reduction in overall P3b latency during the flanker task from pre-test to post-test than WG • EG showed larger increases in ACC and P3b amplitude for heterogeneous trials during the switching task from pre- to post-test compared to WG • Increased attendance was related to higher ACC during the heterogeneous condition of the task-switching task as well as increased P3b amplitude and reduced P3b latency during the incongruent condition of the flanker task

(Continues)

TABLE 2 (Continued)

Study reference (design)	Characteristics of the study sample	Physical fitness	Physical activity/control program			P3b component		Main findings
			Type	Duration	Intensity	Definition	Task	
Hsieh et al. (2017) (NRT)	• *Exercise group* (n = 24, 8.7 ± 1.1y, MET = 1,241.8 ± 758.1, BMI = 17.1 ± 2.9) • *Control group* (n = 24, 8.6 ± 1.1y, MET = 1,090.3 ± 990.2, BMI = 16.4 ± 1.9)	• *Cardiorespiratory fitness* (PACER) • Strength (ball-throwing) • Muscular endurance (1-min curl-ups) • Flexibility (sit-and-reach) • Motor skill (MABC)	• *Exercise group:* gymnastics training • *Control group:* routine daily activities	• 2 sessions of 90-min per week for 8 weeks	• Moderate intensity (HR = 136.4 ± 16.8, 67.9% of HR_{max})	• Peak amplitude and peak latency of within a 300–600 ms post-S2 window • Sites: Fz, Cz, Pz	• Modified delayed match-to-sample test using S1–S2 paradigm • 6 blocks of 30 trials	• Flexibility and motor skills improved from pre- to post-test for the exercise group • The exercise group showed greater improvements in overall ACC than the control group • P3b amplitude at Pz was increased from pre- to post-test for the exercise group compared to the control group regardless of task difficulty
Ludyga et al. (2018) (RCT)	• N = 36 (male = 63.9%, *12–15y*) • *Exercise group* (n = 19, 12.5 ± 0.7y, MVPA = 126.9 ± 48.4, BMI = 19.3 ± 3.2) • *Control group* (n = 16, 12.4 ± 0.7y, MVPA = 103.7 ± 23.1, BMI = 18.6 ± 2.5)	• Object control and locomotor skills (assessed by a motor competence test [Motorische Basiskompetenzen in German])	• *Exercise group:* aerobic and coordinative activities • *Control group*: engage in conversations about recreational activities and everyday school life	• 20-min exercise session, 5 days a week for 8 weeks • Completed 78.6 ± 11.3% of the scheduled sessions	• Moderate intensity (HR = 134.6 ± 9.4, 67.6 ± 4.8% of HR_{max})	• Mean amplitude within 270–414 and 270–474 ms windows for compatible and incompatible trials, respectively • Peak latency was detected within a 270–550 ms window • Sites: Pz, P1/2, POz, CPz	• Stroop task • 4 blocks of 36 trials	• The exercise group showed larger decreases in RT compared to the control group • Greater increases in compatible and incompatible P3b amplitude from pre- to post-test for the exercise group compared to the control group • Larger increases in P3b amplitude were associated with decreased incompatible RT from pre- to post-intervention (p = 0.028)
Ozkaya et al. (2005) (RCT)	• N = 36 (male = 68.2%) • *Endurance* (n = 12, 70.9 ± 3.1y, BMI = 29.1 ± 1.4) • *Strength* (n = 12, 75.8 ± 2.8y, BMI = 31.2 ± 2.9) • *Control group* (n = 12, 72.3 ± 2.1y, BMI = 29.5 ± 1.3)	• Functional fitness (SFT: chair stand, arm curl, chair sit-and-reach, back scratch, 8ft up-and-go, 6 min walk)	• *Control group*: no exercise • *Endurance training:* walking • *Strength training:* hip extensions, knee flexion, seated lower-leg lift, chair squat, arm raise, biceps curl, and abdominal crunch	• *Endurance training*: from 20-min on day 1 to 50-min in week 3. 3 times/week for 9 weeks • *Strength training*: • 3 times/week for 9 weeks	• Aerobic training: 70% of HRR • Strength training: • began at 60% of 1RM and was gradually adjusted by 5% every 2-week until 80% of 1RM	• P3b amplitude was measured as an absolute value between the peak points of N2 and P3b (N2P3). • Peak latency was measured as the time point of P3b amplitude • Sites: Cz, Fz	• 2-stimulus auditory oddball task (Target:Nontarget = 1:4) • The number of trials was not reported	• Both exercise groups improved chair sit-and reach, back scratch, arm curl, chair stand. In addition, endurance group improved 8 feet up-and-go and strength group improved 6-min walk • Strength group showed increased N2P3 amplitude at Fz and Cz from pre- to post-test than endurance group compared to the control group

(Continues)

TABLE 2 (Continued)

Study reference (design)	Characteristics of the study sample	Physical fitness	Physical activity/control program			P3b component		Main findings
			Type	Duration	Intensity	Definition	Task	
Tsai et al. (2017) (RCT)	• $N = 64$ (male = 100%) • *Open-skill* (OS, $n = 22$, 66.9 ± 4.7y, BMI = 23.7 ± 3.6) • *Closed-skill* (CS, $n = 21$, 66.2 ± 4.9y, BMI = 23.8 ± 3.7) • *Control group* ($n = 21$, 65.7 ± 3.5y, BMI = 23.8 ± 3.3)	• *Cardiorespiratory fitness* (VO_{2max} estimated by Rockport 1-mile walk) • Functional fitness (SFPF: chair stand, arm curl, chair sit-and-reach, back scratch, 8ft up-and-	• *OS:* individual table tennis • *CS:* exercise on bicycle or treadmill • *Control group*: exercise for balance and stretching	• 40-min sessions 3 times per week for 24 weeks	• *OS:* not reported • *CS:* 50%–60% HRR during the first 2 weeks and 70%–75% HRR for the remaining weeks	• Mean amplitude and peak latency within a 300−600 ms post-stimulus window • Sites: FZ, Cz, Pz	• Task-switching task: 4 blocks of 56 homogeneous trials and 4 blocks of 56 heterogeneous trials • *N*-back task: 3 blocks of 120 trials for each condition (0-back, 1-back, and 2-back)	• OS increased arm curl, chair stand, and 8-foot up-and-go; CS increased VO_{2max} and decreased weight and BMI • OS and CS showed faster RT in the switch trials after intervention compared to the control group • Only OS showed decreases in overall RT from pre- to post-test • OS and CS showed improved ACC in the 1-back task from pre- to post-test compare to the control group, and CS additionally improved ACC during the 2-back task from pre- to post-test compared to OS and the control group • OS and CS exhibited larger P3b amplitude in the switching task compared to the control group at post-test • OS and CS showed larger P3b amplitude in the *n*-back task compared to the control group at post-test

Note: Abbreviations: 1RM, one-repetition maximum; ACC, response accuracy; BMI, body mass index (kg/m^2); HR, heart rate (beats per minute); HR_{max}, maximum heart rate; HRR, heart rate reserve; MABC, movement assessment battery for children; MET, metabolic equivalents; MVPA, moderate-to-vigorous physical activity (min/day); NRT, nonrandomized trial; PACER, progressive aerobic cardiovascular endurance running; RCT, randomized control trial; RT, response time; SFPF, senior functional physical fitness test; SFT, senior fitness test; VO_{2max}, maximum oxygen consumption (ml/kg/min); VO_{2peak}, peak oxygen consumption (ml/kg/min).

TABLE 3 Summary of the experimental studies examining the acute effect of physical activity intervention on P3b components ($n = 29$)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Cognitive assessment during exercise ($N = 8$)							
Bullock et al. (2015) (WS, CB)	• $N = 12$ (male = 50%, *20.0 ± 1.1y*) • Fitness: $VO_{2max} = 49.1 \pm 10.0$ • BMI = 22.5 ± 3.2	• *Control:* rest in the bike without pedaling • *Low intensity*: pedaling • *High intensity*: pedaling	• *Control*: 45 min • *Low intensity*: 50 min • *High intensity*: 50 min	• *Low intensity*: 40 W ($HR_{achieved} = 114.4 \pm 15.8$) • *High intensity*: 70–120 W ($HR_{achieved} = 147.7 \pm 15.8$)	• Peak latency within a 300−500ms post-stimulus window • Mean amplitude at 391 ± 25ms for P3a and 423 ± 25ms for P3b post-stimulus • Sites: CP1/2, Pz, P3/4, PO3/4	• 3-stimulus visual oddball task • 5 blocks of 200 trials (Target:Distractor:Nontarget = 1:1:8) • Performed during exercise	• High intensity exercise showed faster RT than rest and low intensity exercise • P3b amplitude and latency were not modulated by exercise • P3a latency peaked earlier during both low- and high-intensity exercise compared to rest
Olson et al. (2016) (WS, CB)	• $N = 27$ (male = 59.2%, *20.4 ± 2.0y*) • Fitness: $VO_{2peak} = 42.3 \pm 11.7$ • BMI = 23.2 ± 3.3	• *Control:* Non-exercise seated • *Low intensity*: cycling • *Moderate intensity:* cycling	• *Control*: 31 min • *Low intensity*: 31 min • *Moderate intensity*: 31 min	• *Low intensity*: 40% of VO_{2peak} ($HR_{achieved} = 120$) • *Moderate intensity*: 60% of VO_{2peak} ($HR_{achieved} = 150$)	• Mean amplitude within a 250−500ms post-stimulus window • Sites: Cz, CPz, Pz.	• Modified flanker task: 6.5 min block • Performed at 5, 15, and 25 min after the start of exercise	• Impaired incongruent ACC during both exercise conditions • Improved overall RT during moderate intensity exercise compared to rest and low intensity conditions • Greater P3b amplitudes during both exercise conditions relative to rest
Pontifex and Hillman (2007) (WS, CB)	• $N = 41$ (male = 36.6%, *20.2 ± 1.6y*) • Fitness: $VO_{2max} = 38.3 \pm 7.0$ • BMI = 22.3 ± 2.1	• *Control*: seated rest • *Exercise:* cycling	• *Control*: 6.5 min • *Exercise*: 6.5 min	• 60% HR_{max} ($HR_{achieved} = 114.6 \pm 6.6$)	• Peak amplitude and latency within a 300−600ms post-stimulus window • Sites: Fz, F3/4, F7/8, FCz, FC3/4, FT7/8, Cz, C3/4, T7/8, CPz, CP3/4, TP7/8, Pz, P3/4, P7/8	• Modified flanker task • 1 block of 120 trials • Performed during exercise	• Impaired incongruent ACC during exercise compared to control • Larger P3b amplitude during exercise than control at frontal and fronto-central regions and lateral sites • Longer P3b latency was observed during exercise relative to control
Scanlon et al. (2017)[†] (No control condition)	• $N = 14$ (male = 78.6%, *25.4y*)	• *Stationary biking*	• 3 ~ 3.5min	• Slow and unvarying speed	• P3 component was detected within a 300−430ms post-stimulus window • Sites: not reported	• 2-stimulus auditory oddball task • 3 blocks of 250 trials (Target:Nontarget = 1:4) • Task performed during and 3 min before and after exercise	• No differences in P3b between pre- during- and post-biking were observed

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Torbeyns et al. (2016) (WS, CB)	• $N = 23$ (male = 13.0%, *35.7 ± 10.3y*) • Fitness: $VO_{2peak} = 37.2 \pm 7.7$ • BMI = 23.2 ± 3.0	• *Control*: Sitting on a conventional chair • *Aerobic*: Cycling on the bike desk	• *Control*: 30 min • *Aerobic*: 30 min	• 30% W_{max} ($HR_{achieved} = 116.8 \pm 16.0$)	• Peak amplitude and latency within a 450–550ms post-stimulus window • Sites: Pz, P3/4, P7/8, PO9/10	• Stroop task: 1 block of 60 neutral trials; 1 block of 60 trials for color-naming; 1 block of 60 trials for word-naming • Rosvold continuous performance test (RCPT): 7 min long • Performed during exercise	• General decreases in RT during exercise compared to sitting • No effect on P3b amplitude or latency during Stroop test or RCPT
Vogt et al. (2015) (WS, RAN)	• $N = 22$ (male = 54.5%, *30.27 ± 7.13y*)	• *Control*: passive cycling • *Aerobic:* active cycling	• *Control*: 15 min • *Aerobic*: 15 min • Each condition has no virtual environment(VE), front VE, surrounding VE each for 5 min	• *Control*: automatic drive while rest at the pace of 22km/h • *Aerobic*: self-paced ride ($HR_{achieved} = 120–125$)	• Peak amplitude and latency within a 0–500ms post-stimulus window • ROI: frontal, central, parietal, and occipital sites	• Mental arithmetic task: decisions on which mathematical problem is greater than the other (left vs. right) • Performed during exercise	• No behavioral changes due to exercise were observed • No changes in P3b amplitude or latency due to exercise
Yagi et al. (1999)[†] (No control condition)	• $N = 24$ (male = 50%, *20 ± 2y*)	• *Aerobic*: cycling	• *Aerobic*: 10 min • Each task modality has 1 exercise session	• HR = 130–150 ($HR_{achieved} = 140$)	• Peak amplitude and latency within a 180–600ms post-stimulus window • Site: Pz	• 2-stimulus auditory and visual oddball tasks • 1 block of 200 trials (Target:Nontarget = 1:4) for each modality with counterbalanced order • Performed before, during, and after exercise	• RT decreased during exercise only for both oddball tasks, and the decreases in RT was larger for the visual compared to the auditory oddball task ($p < 0.01$) • P3b amplitude and latency both decreased during exercise for auditory and visual tasks
Zink et al. (2016) (WS, CB)	• $N = 15$ (male = 73.3%, *27.1 ± 2.5y*)	• *Aerobic:* fixed biking • *Aerobic:* free biking • *Control*: rest on the bike	• *Aerobic*: 12 min • *Control*: 12 min	• 12km/h outdoor biking	• Mean amplitude (22 ms around the peak) and peak latency within a 200–600 ms post-stimulus window • Site: Pz	• 3-stimulus auditory oddball task • 1 block 688 trials (92 target, 92 deviant, and 504 standard) • Performed during exercise	• Decreased P3b amplitude in free biking (4.7μV) compared to fixed biking (6.3μV) and rest (6.8μV) conditions
Cognitive assessment after exercise ($N = 23$)							
Chang, Chu, et al. (2017) (WS, CB)	• $N = 30$ (male = 56.7%, *22.7 ± 1.5y*) • Fitness: $VO_{2peak} = 44.5 \pm 8.5$ • IPAQ (MET) = 2,704.5 ± 2098.2 • BMI = 22.2 ± 2.7	• *Aerobic:* cycling ergometer • *Control:* reading exercise-related book	• *Aerobic*: 30 min • *Control*: 30 min	• 60%–70% HRR ($HR_{achieved} = 149.4 \pm 6.4$)	• Peak amplitude and latency within a 300–550 ms post-stimulus window • Sites: Fz, Cz, Pz,	• Stroop task • 6 blocks of 60 trials (38 congruent and 22 incongruent trials) • Performed at 15min after intervention	• Faster RT following the exercise compared to the control condition (444.5 ± 7.0 vs. 484.8 ± 11.0 ms) • Larger P3b amplitude following exercise (13.95 ± 1.06μV) compared to control (12.84 ± 1.04μV)

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Chu et al. (2015) (WS, RAN)	• *N* = 21 (male = 90.5%, *21.5 ± 4.7y*) • Fitness: VO_{2peak} = 55.0 ± 9.8 • BMI = 22.9 ± 2.9	• *Aerobic:* motor-driven treadmill exercise • *Control:* read exercise-related articles	• *Aerobic:* 30 min • *Control*: 30 min	• 65%–75% HR_{max} ($HR_{achieved}$ = 155.5 ± 6.1)	• Peak amplitude and latency within a 250−550 ms window after stop-signal onset. • Sites: Fz, Cz, Pz.	• Stop-signal task • 2 blocks of 200 trials (Stop:Go = 1:3) • Performed at 10min after intervention	• Faster stop signal RT after the exercise compared to the control condition • Exercise session showed larger overall P3b amplitude and longer P3b latency at Pz compared to the control session
Drollette et al. (2014) (WS, CB)	• *N* = 40 (male = 32.5%, *9.7 ± 0.7y*) • *Higher performers* (*n* = 20, 9.8 ± 0.1, VO_{2max} = 40.1 ± 1.6, BMI = 20.3 ± 1.3) • *Lower performers* (*n* = 20, 9.6 ± 0.2, VO_{2max} = 40.5 ± 1.6, BMI = 18.2 ± 1.0)	• *Aerobic:* motor-driven treadmill exercise • *Control:* quiet rest while seated in a chair	• *Aerobic:* 20 min • *Control:* 20 min	• 60%–70% HR_{max}	• Peak amplitude and latency within a 300–600 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz, Oz.	• Modified flanker task • 2 blocks of 100 trials • Performed at 22.5min after intervention when HR returned to within 10% of baseline levels	• Only lower performers improved overall ACC and ACC interference scores following exercise compared to the control condition • Only lower performers showed increased P3b amplitude following exercise compared to the control condition • Both groups showed shorter P3b latency compared to the control condition
Hillman et al. (2003) (WS, CB)	• *N* = 19 (male = 52.6%) • Fitness: VO_{2max} = 48.4 ± 3.0 • BMI = 22.8	• *Aerobic:* motor-driven treadmill exercise • *Baseline:* no intervention	• 30 min	• Somewhat hard on RPE ($HR_{achieved}$ = 162.4 ± 3.6, 83% HR_{max})	• Peak amplitude and latency within a 250−500 ms post-stimulus window • Sites: Fz, Cz, Pz, Oz	• Modified flanker task • 5 blocks of 144 trials • Performed at 48min after exercise when the HR returned to within 10% of baseline levels	• P3b amplitude increased following exercise compared to the baseline (11.5 vs. 9.7) • The increase in P3b latency for the incompatible compared to the neutral condition was observed at baseline but not following exercise
Hillman et al. (2009) (WS, CB)	• *N* = 20 (male = 60%, *9.5 ± 0.5y*) • Fitness: VO_{2max} = 40.1 ± 8.9 • BMI = 18.5 ± 4.7	• *Aerobic:* motor-driven treadmill exercise • *Control:* Seated rest	• *Aerobic:* 20 min • *Control:* 20 min	• 60% HR_{max} ($HR_{achieved}$ = 125.4 ± 1.0)	• Peak amplitude and latency within a 300−600 ms post-stimulus window • Sites: Fz, F1/2, F3/4, F5/6, F7/8, FCz, FC1/2, FC3/4, FC5/6, FT7/8, Cz, C1/2, C3/4, C5/6, T7/8, CPz, CP1/2, CP3/4, CP5/6, TP7/8, Pz, P1/2, P3/4, P7/8	• Modified flanker task • 2 blocks of 100 trials • Performed at 25.5min after intervention when the HR returned to within 10% of baseline levels	• Increased incongruent ACC and decreased ACC interferences after exercise compared to control • Larger overall P3b amplitude after exercise relative to rest at fronto-central, central, and parietal regions • Larger incongruent P3b amplitude following exercise compared to rest at the centro-parietal region

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Jain et al. (2014) (WS, CB)	• *N* = 12 (male = 100%, *18.6 ± 0.9y*) • BMI = 23.6 ± 1.2	• *Exercise:* maximal graded incremental exercise on a treadmill • *Control*: seated rest	• *Exercise*: until exhaustion (8 ± 1 min) • *Control*: 15 min	• Volitional exhaustion, HR within 10 beats per minute of HR_{max}, or RPE ≥ 17 (maximum $HR_{achieved} =$ 192.5 ± 5.1)	• Peak amplitude and latency within a 230−380 ms post-stimulus window • Sites: Fz, Cz, Pz	• 2-stimulus auditory and visual oddball tasks (Target:Nontarget = 1:4) • 40 target trials excluding rejection errors • Performed once HR returned to within 10% of baseline levels	• Exercise showed reduced RT during auditory and visual tasks compared to baseline • Exercise resulted in increased P3b amplitude and shorter latency at all three sites (Fz, Cz, Pz, *ps*<0.05) compared to the baseline
Kamijo, Nishihira, Hatta, Kaneda, Wasaka, et al. (2004) (WS, NCB)	• *N* = 12 (male = 100%, *22−33y*)	• *High intensity cycling* • *Medium intensity cycling* • *Low intensity cycling* • *Baseline session*	• The duration obtained for each subject in the high-intensity exercise was used for medium and low intensity exercises (18.1 ± 0.6 min).	• *High intensity*: until volitional exhaustion ($HR_{achieved}$ = 190.2 ± 3.3) • *Medium intensity*: 12–14 RPE ($HR_{achieved}$ = 118.2 ± 4.5) • *Low intensity*: 7–9 RPE ($HR_{achieved}$ = 84.4 ± 4.2)	• Peak amplitude and latency within a 250−500 ms post-imperative stimulus window • Sites: Fz, Cz, Pz	• Go/Nogo task using a S1–S2 paradigm • 1 block of 60 trials • Performed less than 3 min after exercise	• Mean P3b amplitude decreased following high intensity exercise than medium intensity exercise at all sites and the baseline at Fz and Pz • Mean P3b amplitude after medium intensity exercise was larger than the baseline at Fz and Cz • Nogo P3b amplitude after high intensity exercise was smaller than medium intensity exercise at all sites and the baseline at Cz • No-go P3b amplitude after medium intensity exercise was larger than the baseline at all sites
Kamijo et al. (2007) (WS, RAN)	• *N* = 12 (male = 100%, *25.7 ± 0.7y*)	• *High intensity cycling* • *Medium intensity cycling* • *Low intensity cycling* • *Baseline session*	• *Exercise:* 20 min	• *High intensity*: RPE = 15 ($HR_{achieved}$ = 149.3 ± 2.3) • *Medium intensity*: RPE = 13 ($HR_{achieved}$ = 134.2 ± 2.1) • *Low intensity*: RPE = 11 ($HR_{achieved}$ = 118.2 ± 2.3)	• Peak amplitude and latency within a 300−600 ms post-stimulus window • Sites: Fz, Cz, C3, C4, Pz	• Modified flanker task • Performed less than 3 min after exercise	• All exercise conditions improved overall RT • Increased P3b amplitude following low and moderate intensity exercise compared to baseline
Kamijo et al. (2009) (WS, CB)	• *N* = 24 (male = 100%) • *Young males* (*n* = 12, 21.8 ± 0.6y, $VO_{2max} =$ 52.2 ± 2.1) • *Old males* (*n* = 12, 65.5 ± 1.5y, $VO_{2max} =$ 32.4 ± 1.3)	• *Aerobic*: cycling ergometer • *Baseline:* no intervention	• *Aerobic*: 20 min • *Control*: Not applicable	• *Light*: 30% workload of VO_{2max} ($HR_{achieved} =$ 55% HR_{max}) • *Moderate*: 50% workload of VO_{2max} ($HR_{achieved} =$ 74% HR_{max})	• Peak amplitude and latency within a 300−750 ms post-stimulus window • Sites: Fz, Cz, Pz,	• Modified flanker task • 1 block of 160 trials • Performed less than 2 min after intervention	• Moderate exercise resulted in faster RT than light exercise (*p* = 0.02) and marginally faster RT than control • Larger P3b amplitude following moderate exercise than baseline only in young males • Shorter P3b latency following light and moderate exercise than baseline for both young and old participants

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Kao, Westfall, Soneson, et al. (2017) (WS, CB)	• $N = 64$ (male = 42.2%, *19.2 ± 0.8y*) • Fitness: $VO_{2max} = 48.6 \pm 10.0$ • BMI = 23.8 ± 3.0	• *Aerobic*: treadmill exercise • *High-intensity interval training (HIIT)*: treadmill exercise • *Control*: seated rest	• *Aerobic*: 20 min • *HIIT*: 9 min • *Control*: 20 min	• *Aerobic*: 60%–70% HR_{max} ($HR_{achieved}$ = 66% HR_{max}) • *HIIT*: 90% HR_{max} ($HR_{achieved}$ = 91% HR_{max})	• Mean amplitude and peak latency of within a 250–600 ms post-stimulus window • ROIs: fronto-central (Fz, Fz, F1/2, FCz, FC1/2), centro-parietal (Cz, C1/2, CPz, CP1/2), parieto-occipital (Pz, P1/2, POz, PO3/4)	• Modified flanker task • 2 blocks of 100 trials • Performed at 20 min following intervention	• Faster overall RT following aerobic and HIIT than rest. Increased ACC for incongruent trials following HIIT compared to aerobic and rest • Larger P3b amplitude after aerobic compared to rest and HIIT • Decreased P3b amplitude and P3b latency after HIIT compared to rest
Ludyga et al. (2017) (WS, CB)	• $N = 18$ (male = 55.6%, *13.5 ± 1.3y*) • Fitness: power output = 2.5 ± 0.5 watt/kg • BMI = 20.2 ± 3.3	• *Aerobic*: cycling • *Coordinative:* object control skills and bilateral coordination • *Control:* Watching a documentary on exercise behavior in adults	• *Aerobic*: 20 min • *Coordinative*: 20 min • *Control*: 20 min	• *Aerobic*: 65%–70% HR_{max} ($HR_{achieved}$ = 139.4 ± 2.1) • *Coordinative*: not prescribed ($HR_{achieved}$ = 131.3 ± 11.6)	• Mean amplitude (40 ms around the peak) and fractional latency at 70% of the peak amplitude within a 250–600 ms post-stimulus window • Sites: Pz, P1/2, P3/4	• Modified flanker task • 4 blocks of 40 trials • Performed before and at 10 min after intervention	• Greater decrease of RT following both exercise sessions compared to the control condition ($ps < 0.001$) • Larger P3b increases in amplitude after both exercise sessions compared to the control condition ($ps < 0.001$) • No significant differences in changes pre-post in P3b latency
Magnie et al. (2000)* (No control condition)	• $N = 20$ (male = 100%, *18–30y*) • *Cyclists* (n = 10, 21.2y, $VO_{2max} = 63.8 \pm 7.7$) • *Sedentary* (n = 10, 22.9y, $VO_{2max} = 47.4 \pm 7.0$)	• Maximal continuous incremental exercise on a cycle ergometer	• Until exhaustion	• Until exhaustion	• Peak amplitude and latency within a 250–400 ms post-stimulus window • Site: Fz, Cz, Pz	• 2-stimulus auditory oddball (Target:Nontarget = 1:4) • 2 blocks of 20 artifact-free target stimulus trials	• Increased P3b amplitude (1.4 – 2.3μV, $F_{(1,19)} = 12.24$, $p = 0.003$) and reduced P3b latency (17–20 ms, $F_{(1,19)} = 11.19$, $p = 0.004$) after exercise compared to pre-test
O'Leary et al. (2011) (WS, CB)	• $N = 36$ (male = 50%, *21.2 ± 1.5y*) • Fitness: $VO_{2max} = 45.2 \pm 5.9$ • BMI = 23.3 ± 3.0	• *Treadmill*: aerobic walk • *MarioKart*: Car race video games • *Wii fit*: Three 6-min aerobic games • *Control:* Seated rest	• *Treadmill*: 20 min • *MarioKart*: 20 min • *Wii fit*: 20 min • *Control*: 20 min	• *Treadmill*: 60% HR_{max} ($HR_{achieved}$ = 117.1 ± 1.5)	• Peak amplitude and latency within a 300–520 ms post-stimulus window • Sites: Fz, F1/2, F3/4, FCz, FC1/2, FT3/4, Cz, C1/2, C3/4, CPz, CP1/2, CP3/4, Pz, P1/2, P3/4	• Modified flanker task • 1 block of 200 trials • Performed (22.2 ± 0.6 min) after exercise once HR returned to within 10% of pre-exercise levels	• Decreased RT interference scores following exercise compared to rest and MarioKart • Greater P3b amplitude after treadmill walking relative to rest. amplitude compared to rest
Pontifex et al. (2013) (WS, CB)	• $N = 20$ (male = 70%, *9.8 ± 0.1y*) • BMI = 20.0 ± 1.2	• *Aerobic:* exercise on a treadmill • *Control:* seated reading	• *Aerobic*:20 min • *Control*: 20 min	• *Aerobic*: 65%–75% HR_{max} ($HR_{achieved}$ = 132.1 ± 10.3)	• Mean amplitude (50 ms around the P3 peak) and peak latency within a 300–700 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz, POz, Oz	• Modified flanker task • 2 blocks of 100 trials for each stimulus-response mapping (compatible and incompatible) condition • Performed 16 min after the HR returned to within 10% of baseline levels	• Increased ACC following exercise than control • Larger P3b amplitude after exercise compared with after reading • Shorter P3b latency at the FCz, Cz, and CPz electrode site following exercise compared to control

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Physical activity/Control program: Duration	Physical activity/Control program: Intensity prescribed (achieved)	P3b component: Definition	P3b component: Task	Main findings
Pontifex et al. (2015) (WS, CB)	• *N* = 36 (male = 44.4%, *19.3 ± 0.9y*)	• *Aerobic:* exercise on a treadmill • *Control:* seated rest	• *Aerobic*: 20 min • *Control*: 20 min	• *Aerobic*: 70% HR_{max} ($HR_{achieved}$ = 138.8 ± 11.0)	• Mean amplitude (50 ms) and peak latency of positive-going peak within 300–700 ms post-stimulus • Site: Fz, FCz, Cz, CPz, Pz, POz, Oz	• 3-stimulus visual oddball task • 3 blocks of 175 trials (Target:Distractor:Nontarget = 12:12:76) • Performed 20 min prior to and 3 ~ 5 min following intervention	• No changes in ACC or RT following the exercise compared to the sitting condition • Larger P3b amplitude post-exercise compared to post-sitting where no such differences between conditions at the pre-test • P3b amplitude maintained from pre- to post-exercise but decreased from pre- to post-sitting • No exercise-related changes in P3a amplitude and latency were observed
Popovich and Staines (2015) (No control condition)	• *N* = 16 (male = 40%, 25.2y)	• *Aerobic:* pedaling on the ergometer until target HR and maintain this exercise intensity	• *Aerobic*: 20 min	• 60% HR_{max}	• Peak amplitude and latency within a 300–600 ms post-stimulus window • Sites: FCz, Cz, CPz.	• 2-stimulus tactile oddball task • 6 blocks of 120 trials (Target:Nontarget = 1:5) • Performed 5 min after the HR returned to within 10% of pre-experimental condition levels	• No exercise-related changes in P3b amplitude and latency were observed
Scanlon et al. (2017)[†] (No control condition)	• *N* = 14 (male = 78.6%, *25.4y*)	• *Stationary biking*	• 3 ~ 3.5min	• Slow and unvarying speed	• P3 component was detected within a 300–430 ms post-stimulus window • Sites: not reported	• 2-stimulus auditory oddball • 3 blocks of 250 trials (Target:Nontarget = 1:4) • Performed during and 3 min before and after exercise	• No differences in P3b between pre- during- and post-biking were observed
Scudder et al. (2012) (WS, CB)	• *N* = 37 (male = 51.4%, *19.7 ± 1.3y*) • Fitness: VO_{2max} = 47.2 ± 7.3 • BMI = 23.1 ± 2.6	• *Aerobic:* motor-driven treadmill exercise • *Control:* read the university daily news paper	• *Aerobic*: 30 min • *Control*: 30 min	• 60% HR_{max} ($HR_{achieved}$ = 117.2 ± 5.7)	• Peak amplitude and latency within a 300–600 ms post-stimulus window • Sites: Fz, FCz, Cz, CPz, Pz	• Modified AX-CPT task • 2 blocks of 175 trials for each of 3 conditions (AX−64, AY−64, BX−64), with each condition consisting of 64% of AX, AY, and BX, espectively. • Performed 20–25 min after intervention	• Exercise increased ACC during AX (i.e., target) trials compared to control • Exercise increased P3b amplitude across all conditions for probes of AY trials at Cz and CPz sites, *ts*(36) ≥ 2.9, *ps* ≤ 0.01, *ds* ≥ 0.33, and for AY and AX trials at the Pz site, *ts*(36) ≥ 2.6, *ps* ≤ 0.015, *ds* ≥ 0.30, when compared to the control session.

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Stroth et al. (2009)* (WS, RAN)	• N = 33 (male = 60.6%, *14.2 ± 0.5y*) • *Higher-Fit* (n = 17, 14.2 ± 0.4y, Watt/BMI = 8.8 ± 1.2) • *Lower-Fit* (n = 16, 14.3 ± 0.6y, Watt/BMI = 6.7 ± 0.9)	• *Aerobic:* watched a movie while cycling workout • *Control:* watched a movie while resting	• *Aerobic*: 20 min • *Control*: 20 min	• 60% of HR_{max}	• Peak amplitude and latency within a 340–440 ms post-stimulus window • Sites: C3/4	• Go/Nogo-Flanker task • 5 blocks of 120 trials (300 Go-trials; 300 Nogo-trials) • Performed at 20 min following intervention	• Exercise did not affect task performance, P3b amplitude, and P3b latency ($ps > 0.40$)
Tsai, Wang, et al. (2014)* (BS)	• N = 60 (male = 100%) • *Exercise intervention in lower-fit* (EI_L) (n = 20, 23.1 ± 2.2y, VO_{2max} = 36.0 ± 3.6, IPAQ = 2,366.0 ± 1,017.7, BMI = 24.5 ± 4.5) • *Exercise intervention in higher-fit* (EI_H) (n = 20, 22.2 ± 2.2y, VO_{2max} = 58.0 ± 6.7, IPAQ = 5,857.1 ± 2,768.9, BMI = 22.2 ± 2.3) • *Non-Exercise intervention* (NEI) (n = 20, 22.2 ± 1.7y, VO_{2max} = 46.6 ± 9.4, IPAQ = 4,163.4 ± 2,904.4, BMI = 22.3 ± 1.9)	• *Aerobic:* motor-driven treadmill exercise • *Control:* read magazines	• *Aerobic*: 30 min • *Control*: 30 min	• 60% of VO_{2max}	• Peak amplitude and latency within a 300–700 ms post-stimulus window • Sites: Cz, Pz	• Modified visuospatial attention task • 3 blocks of 90 trials (54 trials in valid cue condition, 27 trials in invalid cue condition, 9 trials in neutral condition) • Performed before and at 15–20 min after intervention	• Both exercise groups improved RT from the pre- to post-test whereas NEI did not • EI_H (12.27 μV) showed larger P3b amplitude than NEI (7.14 μV) after intervention • Only EI_H showed increased P3b amplitude from pre- to post-intervention ($p = 0.001$) • No correlation between changes in brain-derived neurotrophic factor (BDNF) and P3b amplitude from pre- to post-intervention in any group
Tsai, Wang, et al. (2014) (BS)	• N = 60 (male = 100%) • *Moderate-intensity group* (n = 20, 23.2 ± 2.5y, IPAQ = 1,091.6 ± 459.5, BMI = 20.8 ± 1.5) • *High-intensity group* (n = 20, 22.4 ± 2.4y, IPAQ = 888.2 ± 292.7, BMI = 21.5 ± 1.8) • *Non-Exercise Intervention* (n = 20, 23.2 ± 2.1y, IPAQ = 933.2 ± 241.0, BMI = 22.0 ± 2.6)	• *Resistance:* bench press, biceps curls, triceps extension, leg press, vertical butterflies, leg extensions • *Control:* read magazines	• *Resistance*: 40 min • *Control*: 45 min	• Moderate-intensity: 50% of 1RM • High-intensity: 80% of 1 RM	• Peak amplitude and latency within a 250–500 ms post-stimulus window for Go-P3 • Peak amplitude and latency within a 350–550 ms post-stimulus window for NoGo-P3 • Sites: Fz, Cz, Pz,	• Go/Nogo-Flanker • 2 blocks of 200 trials (200 go-trials and 200 Nogo-trials) • Performed before and after intervention (5 min after exercise or immediately after reading)	• Both intervention groups showed improved overall RT and incongruent-no-go ACC compared to the control group ($ps < 0.05$) • High-intensity (pre- vs. post-exercise: 8.24 ± 6.98 vs.13.58 ± 7.35μV, $p < 0.001$) and moderate-intensity (pre- vs. post-exercise: 8.40 ± 4.86 vs.14.91 ± 4.49μV, $p < 0.001$) groups exhibited increased P3b amplitude from pre- to post-test, but NEI did not change P3b amplitude from pre- to post-test

(Continues)

TABLE 3 (Continued)

Study reference (design)	Characteristics of the study sample	Physical activity/Control program: Type	Duration	Intensity prescribed (achieved)	P3b component: Definition	Task	Main findings
Tsai, Wang, et al. (2016)* (BS)	• $N = 60$ (male = 100%) • *Exercise intervention in lower-fit* (EI_L) ($n = 20$, 22.7 ± 1.9y, $VO_{2max} =$ 36.9 ± 3.8, IPAQ = 1,167.7 ± 1,272.7, BMI = 23.3 ± 2.7) • *Exercise intervention in higher-fit* (EI_H) ($n = 20$, 22.2 ± 2.2y, $VO_{2max} =$ 59.8 ± 7.5, IPAQ = 5,002.0 ± 2,843.9, BMI = 22.3 ± 2.1) • *-Non-Exercise intervention* (NEI) ($n = 20$, 22.6 ± 1.7y, $VO_{2max} =$ 47.7 ± 8.9, IPAQ = 2,093.2 ± 1,232.2, BMI = 22.2 ± 1.9)	• *Aerobic:* motor-driven treadmill exercise • *Control*: read magazines	• *Aerobic*: 30 min • *Control*: 47 min	• 60% of VO_{2max}	• Peak amplitude within a 250−600 ms post-stimulus window • Site: Pz	• Task-switching task • 1 block of 64 trials for each homogeneous condition and 4 heterogeneous blocks of 64 trials • Performed before and after intervention (15–20 min after exercise and immediately after control condition)	• Both intervention groups showed reduced RT and inverse efficiency in pure, switching, and non-switching conditions after exercise compared to before exercise • Only EI_H group showed decreased switching cost from pre- and post-test • EI_H group exhibited a larger P3b amplitude after acute exercise in the non-switching ($p = 0.010$, $d = 0.50$) and switching ($p < 0.001$, $d = 0.99$) trials compared with before exercise • No correlations between BDNF and P3b amplitude
Yagi et al. (1999)† (No control condition)	• $N = 24$ (male = 50%, *20 ± 2y*)	• *Aerobic*: cycling	• *Aerobic*: 10 min • Each task modality has 1 exercise session	• HR = 130–150 ($HR_{achieved} =$ 140)	• Peak amplitude and latency within a 180−600ms post-stimulus window • Site: Pz	• 2 stimulus auditory and visual oddball tasks • 1 block of 200 trials (Target:Nontarget = 1:4) for each modality with counterbalanced order • Performed before, during, and after exercise	• No changes in RT or P3b indices were observed at the post-exercise test compared to as the pre-exercise rest

Note: Abbreviations: 1RM, one-repetition maximum; ACC, response accuracy; BMI, body mass index (kg/m^2); BS, between-subject design; CB, counterbalanced session orders; W_{max}, external power; IPAQ, International Physical Activity Questionnaire; HR, heart rate (beats per minute); $HR_{achieved}$, heart rate achieved during exercise intervention; HR_{max}, maximum heart rate; HRR, heart rate reserve; MET, metabolic equivalent; NCB, noncounterbalanced session orders; RAN, randomized session orders; ROI, region of interest; RT, response time; RPE, rating of perceived exertion; VO_{2max}, maximum oxygen consumption (ml/kg/min); VO_{2peak}, peak oxygen consumption (ml/kg/min); WS, within-subject design.

*Studies also investigating the cross-sectional association of physical activity/fitness with P3b.

†Studies reporting P3b both during and postexercise.

TABLE 4 Categories of cognitive tasks used to examine P3b

	Cognitive control tasks		
Inhibitory control	**Working memory**	**Cognitive flexibility**	**Attention tasks**
Flanker task ($n = 20$)	Sternberg task ($n = 1$)	Task-switching task ($n = 10$)	Simple RT task ($n = 1$)
Go/no-go task ($n = 1$)	*N*-back task ($n = 1$)		Discrimination task ($n = 1$)
Go/no-go flanker task ($n = 3$)	AX-CPT task ($n = 2$)		Vigilance task ($n = 2$)
Stroop task ($n = 5$)	Match-to-sample task ($n = 2$)		Two-stimulus oddball task ($n = 16$)
Stop-signal task ($n = 1$)	Mental arithmetic task ($n = 2$)		Three-stimulus oddball task ($n = 5$)
Spatial priming task ($n = 1$)			Visuospatial attention task ($n = 4$)
			Attentional blink task ($n = 1$)

2003; Polich & Lardon, 1997). Two studies (10.5%) found improved task performance for active compared to inactive older adults, while no differences in P3b were observed between groups (Getzmann, Falkenstein, & Gajewski, 2013; Hawkes, Manselle, & Woollacott, 2014). One study (5.3%) found no effect of physical activity on both P3b and behavioral indices during a simple response time (RT) task in 19- to 86-year-old participants (Berchicci, Lucci, Perri, Spinelli, & Di Russo, 2014). No research in children was available. The pattern of associations of P3b and behavior with chronic physical activity as well as cardio-respiratory fitness and exercise interventions across studies are shown in Figure 4.

Across studies, evidence supported a relationship of physical activity on P3b from early to late adulthood, with increased physical activity related with larger P3b amplitude (Chang et al., 2017; Chang, Huang, et al., 2013; Dai et al., 2013; Fong et al., 2014; Hillman et al., 2004, 2006; Polich & Lardon, 1997; Tsai & Wang, 2015; Wang & Tsai, 2016; see example in Figure 5b), shorter P3b latency (Chang, Huang, et al., 2013; Fong et al., 2014; Hillman et al., 2004, 2006; Kamijo & Takeda, 2009), or greater neural efficiency as reflected by a larger capacity for upregulating P3b amplitude when task demand increased (Gajewski & Falkenstein, 2015; Kamijo & Takeda, 2010). These associations may be moderated by age—as topographic shifts in the expression of P3b on the scalp differ with age (McDowell et al., 2003) as well as for open-skill compared to closed-skill activities, which were associated with larger increases in P3b amplitude (Chang et al., 2017; Tsai & Wang, 2015; Tsai, Wang, et al., 2016) and more localized scalp distribution of P3b amplitude (Huang, Lin, Hung, Chang, & Hung, 2014). Although null associations of physical activity with P3b were found in three studies, these findings may be related to methodological decisions such as unspecified windows for measuring P3b (Hawkes et al., 2014) or tasks designed to elicit different subcomponents of P3 complex (Getzmann et al., 2013) or to only assess simple RT (Berchicci et al., 2014).

3.3 | Cross-sectional evidence of an association of cardio-respiratory fitness with P3b

Among the 21 studies reviewed, only one (4.8%) investigated muscular fitness in relation to P3b, while all others (95.2%) examined cardio-respiratory fitness. Therefore, the current review focused on the associations between cardio-respiratory fitness and P3b (the study investigating muscular fitness is included in Table 1). The majority, 14 of the 20 (70%) cardio-respiratory fitness studies, showed positive associations with P3b in response to cognitive control and attention tasks (Hawkes et al., 2014; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Kamijo & Masaki, 2016; Luque-Casado et al., 2016; Pontifex, Hillman, & Polich, 2009; Pontifex et al., 2011; Song et al., 2016; Tsai, Chen, et al., 2014; Tsai, Pan, Chen, Wang, & Chou, 2016; Wang, Shih, & Tsai, 2016; see example in Figure 5b), despite no associations of cardio-respiratory fitness with behavioral performance in three of these 14 (21.4%) studies (Dustman et al., 1990; Emmerson, Dustman, Shearer, & Turner, 1989; Hillman, Weiss, Hagberg, & Hatfield, 2002). Three studies (15%) found no associations of cardio-respiratory fitness with either P3b or behavioral outcomes in young adults and adolescents (Magnie et al., 2000; Scisco, Leynes, & Kang, 2008; Stroth et al., 2009). Three studies (15%) showed that cardio-respiratory fitness was negatively associated with P3b, despite a positive association with behavioral performance

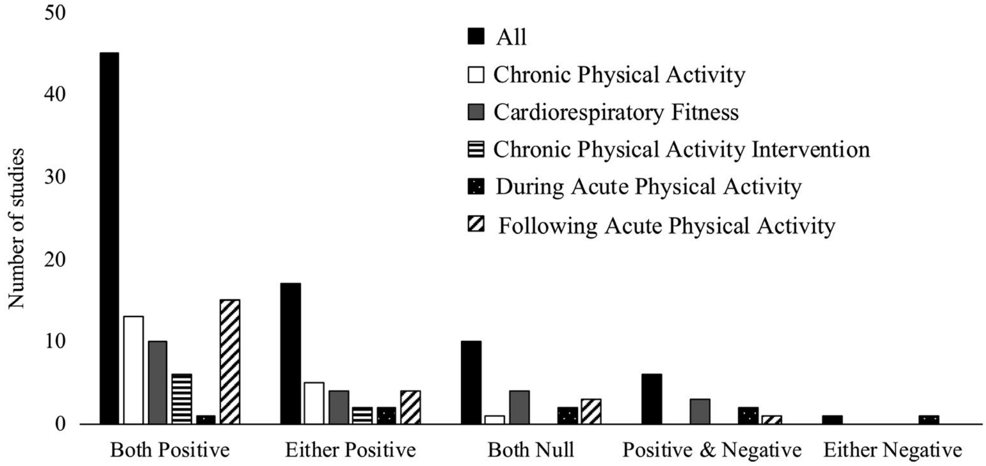

FIGURE 4 Number of studies within the following five categories: (a) positive associations with both P3b and behavior, (b) positive associations with either P3b or behavior, (c) null associations with both P3b and behavior, (d) positive associations with P3b and negative associations with behavior or vice versa, (e) negative associations with either P3b or behavior. None of the reviewed studies showed negative associations with both P3b and behavior. Positive indicates increased/greater response accuracy or P3b amplitude as well as decreased/lower response time or P3b latency, while a negative value is reflected by decreased/lower response accuracy or P3b amplitude as well as increased/greater response time or P3b latency

(Moore, Drollette, Scudder, Bharij, & Hillman, 2014; Moore et al., 2013; Wu & Hillman, 2013).

Across age groups, evidence supports a relationship between cardiorespiratory fitness and the P3b-ERP component, with increased cardiorespiratory fitness associating with larger P3b amplitude (Hawkes et al., 2014; Hillman et al., 2005; Hillman, Buck, et al., 2009; Kamijo & Masaki, 2016; Luque-Casado et al., 2016; Pontifex et al., 2009, 2011; Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016; Wang et al., 2016) or shorter P3b latency (Dustman et al., 1990; Emmerson et al., 1989; Hillman et al., 2005, 2002; Pontifex et al., 2011; Wang et al., 2016). Further, a few studies indicated that cardiorespiratory fitness-related increases in P3b amplitude might be more robust in healthy weight (Song et al., 2016) and younger (Pontifex et al., 2009) compared to obese weight and older adults. Three studies reported null associations between cardiorespiratory fitness and P3b, although these findings may be confounded with participant selection (i.e., trained cyclists vs. sedentary individuals, Magnie et al., 2000), the inclusion of a broader electrode array rather than a focus on midline electrodes (Scisco et al., 2008; Stroth et al., 2009), or the task involving feedback-related processing (Stroth et al., 2009). The findings from three studies indicating negative associations between cardiorespiratory fitness and P3b may be confounded with the inflated Type I error due to the exploration on outcomes related to single-trial P3b and ex-Gaussian function analyses (Moore et al., 2013). Further, unique P3b-eliciting tasks that required efficient allocation of attentional resources to multiple stimuli within a single trial (Wu & Hillman, 2013) or to verification on single-digit arithmetic problems (Moore et al., 2014) are likely confounded as well.

3.4 | Findings from experimental studies on the chronic effect of physical activity on P3b

3.4.1 | Intervention efficacy

Of a total of eight intervention studies, three (37.5%) studies in preadolescent/adolescent children provided heart rate data or the attendance rate to quantify the dose of physical activity (Chang, Tsai, Chen, & Hung, 2013; Hillman et al., 2014; Ludyga, Gerber, Kamijo, Brand, & Puhse, 2018). Irrespective of age, six (75%) of the eight studies demonstrated the efficacy of the physical activity intervention by showing greater improvements in physical fitness for the intervention group compared to the control group (Chang, Tsai, et al., 2013; Chuang, Hung, Huang, Chang, & Hung, 2015; Hillman et al., 2014; Hsieh et al., 2017; Ozkaya et al., 2005; Tsai et al., 2017). Two (25%) studies did not assess the extent to which the physical activity intervention induced changes in physical fitness (Cetin et al., 2010; Ludyga et al., 2018).

3.4.2 | Physical activity and P3b

Results across eight (100%) studies showed modulation of P3b following physical activity interventions occurring at least twice per week for a duration ranging from 8 weeks to 9 months (see example in Figure 5c). In older adults, closed-skill (aerobic) and open-skill (table tennis) training at moderate intensities increased P3b amplitude (Tsai et al., 2017). Aerobic and dance activities also decreased P3b latency (Cetin et al., 2010; Chuang, Hung, Huang, Chang, & Hung, 2015). P3b amplitude was found to increase following

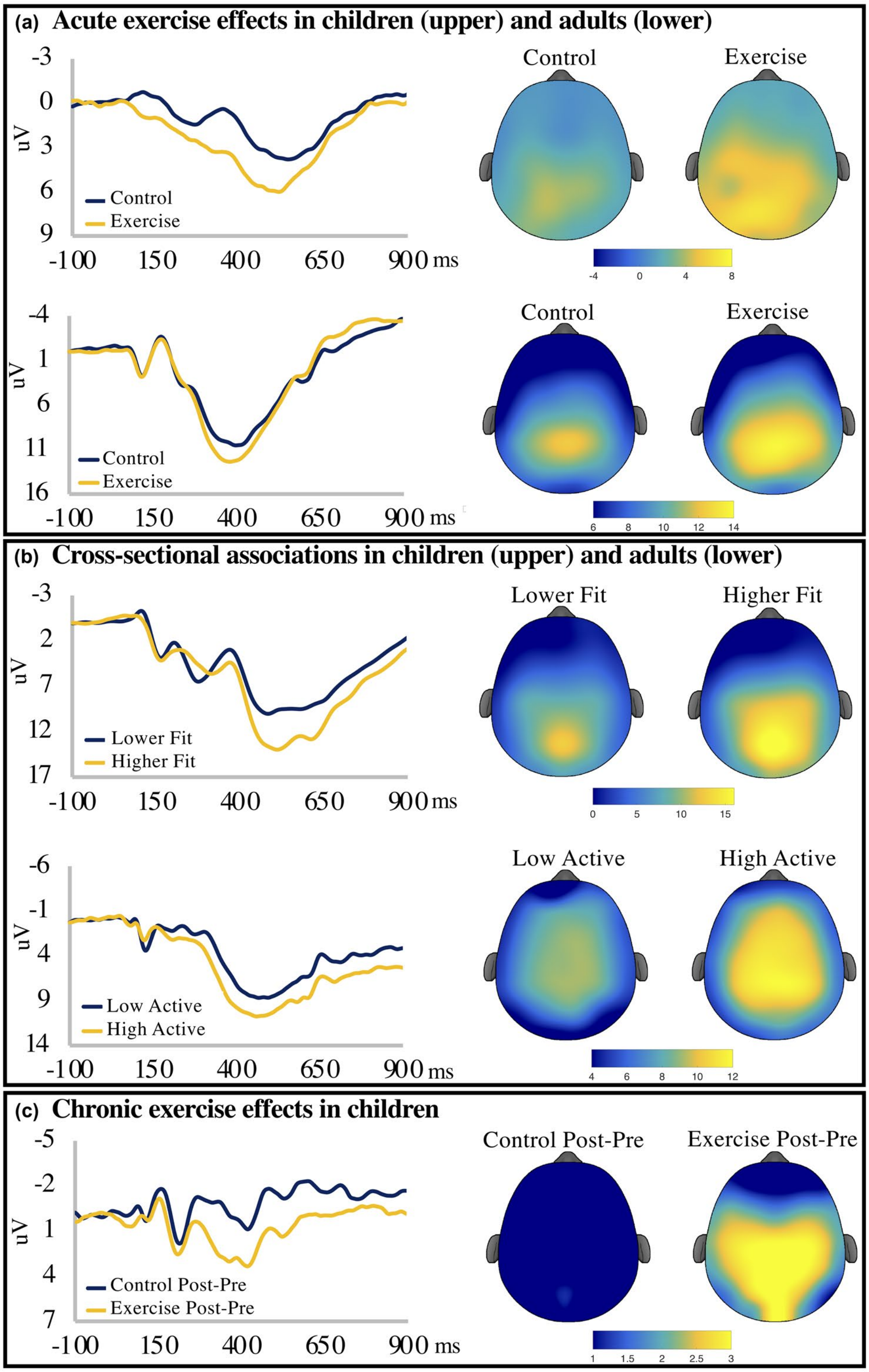

FIGURE 5 Grand-averaged waves at selected hot spots based on the scalp topography of P3b amplitude collapsed across congruency trial types during the flanker tasks in studies using different experimental designs. (a) Acute exercise effects on P3b in children (Hillman, Pontifex et al., 2009) and adults (Hillman et al., 2003). (b) Cross-sectional associations of childhood cardiorespiratory fitness (Hillman, Buck et al., 2009) and late adulthood physical activity with P3b (Hillman et al., 2004). (c) Chronic exercise effects on the changes of P3b from pretest to posttest in children (Hillman et al., 2014)

9 weeks of strength activity intervention with adaptive intensity, whereas endurance physical activity intervention with adaptive duration of each session did not result in such changes in P3b amplitude (Ozkaya et al., 2005). Research in preadolescent and adolescent children also showed that low to moderate-to-vigorous intensity physical activity

interventions increased P3b amplitude (Chang, Tsai, et al., 2013; Hillman et al., 2014; Hsieh et al., 2017; Ludyga et al., 2018) and shortened P3b latency (Chang, Tsai, et al., 2013).

One study (12.5%) demonstrated a dose-response relationship between physical activity and the P3b-ERP by observing that increased attendance during a physical activity intervention was associated with increased P3b amplitude and decreased P3b latency (Hillman et al., 2014). Notably, the observed increases in amplitude and decreases in latency of P3b during cognitive control tasks corresponded with improved behavioral performance (increased accuracy and/or shorter RT) across studies (Chang, Tsai, et al., 2013; Chuang et al., 2015; Hillman et al., 2014; Hsieh et al., 2017; Ludyga et al., 2018; Tsai et al., 2017), with larger increases in P3b amplitude following the intervention associating with greater improvements in RT (Ludyga et al., 2018).

3.5 | Experimental studies on the acute effect of physical activity on P3b

3.5.1 | Intervention efficacy

Twenty of the 29 reviewed studies (69%) reported heart rate data as the measure of intensity during interventions, while the remaining nine studies did not provide any physiological or self-report data to verify the manipulation of exercise intensity (31%). Of the 29 studies, 15 (51.7%), 14 (48.3%), and 7 (22.6%) investigated low, moderate, and high intensity exercise, respectively. Seven (24.1%) of these studies investigated at least two exercise intensities.

3.5.2 | P3b modulation during an acute bout of physical activity

The results from eight studies investigating the effects of physical activity on P3b during the physical activity bout were mixed despite all incorporating adult populations. Four of these eight studies (50%) found that light and/or moderate intensity exercise increased amplitude (Olson et al., 2016; Pontifex & Hillman, 2007) and increased latency (Pontifex & Hillman, 2007) during cognitive control tasks or decreased amplitude (Yagi, Coburn, Estes, & Arruda, 1999; Zink, Hunyadi, Van Huffel, & De Vos, 2016) and decreased latency during attention tasks (Yagi et al., 1999). The other four studies (50%) showed unchanged P3b indices during exercise at light or moderate intensities (Bullock, Cecotti, & Giesbrecht, 2015; Scanlon, Sieben, Holyk, & Mathewson, 2017; Torbeyns et al., 2016; Vogt, Herpers, Scherfgen, Strueder, & Schneider, 2015). The behavioral findings from five studies (62.5%) indicated faster (Bullock et al., 2015; Olson et al., 2016; Torbeyns et al., 2016; Yagi et al., 1999) or less accurate (Olson et al., 2016; Pontifex & Hillman, 2007) responding on cognitive control and attention tasks during exercise, while three studies (37.5%) showed unchanged task performance (Scanlon et al., 2017; Vogt et al., 2015; Zink et al., 2016). The discrepant findings may be due to differences in the duration of the exercise relative to when the P3b assessment began and the dose of exercise across studies as well as the exposure of virtual (Vogt et al., 2015) or outdoor environments (Zink et al., 2016).

3.5.3 | P3b modulation following an acute bout of physical activity

Results from 19 of 23 (82.6%) reviewed studies showed acute physical activity-induced changes in P3b activation following the cessation of the bout. Fifteen studies (65.2%) also showed improved behavioral performance on cognitive tasks. These findings were mainly conducted in healthy weight adults of moderate to high levels of cardiorespiratory fitness, with the exception of lower fit groups included in two studies (Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016). Specifically, increased P3b amplitude and/or decreased P3b latency were found across cognitive domains, age, and health status (Chang, Alderman, et al., 2017; Chu, Alderman, Wei, & Chang, 2015; Drollette et al., 2014; Hillman, Pontifex et al., 2009; Hillman, Snook, & Jerome, 2003; Jain, Jain, Jain, & Babbar, 2014; Kamijo et al., 2009; Kamijo, Nishihira, Hatta, Kaneda, Kida, et al., 2004; Kamijo, Nishihira, Hatta, Kaneda, Wasaka, et al., 2004; Kamijo, Nishihira, Higashiura, & Kuroiwa, 2007; Magnie et al., 2000; O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011; Pontifex, Parks, Henning, & Kamijo, 2015; Pontifex et al., 2013; Scudder, Drollette, Pontifex, & Hillman, 2012; Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016) following acute bouts of aerobic exercise compared to following a nonexercise control condition (see example in Figure 5a). Similar effects were observed when the single bout of physical activity was delivered by interval (Kao, Westfall, Soneson, Gurd, & Hillman, 2017), resistance (Tsai, Wang, et al., 2014), and coordination exercise (Ludyga et al., 2017). However, a few studies reported that the acute effects on P3b following a physical activity bout were observed in individuals only with higher fitness levels (Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016), with lower cognitive capacity (Drollette et al., 2014) or at younger ages (Kamijo et al., 2009). Further, the relationship between the intensity of acute aerobic physical activity and P3b amplitude was described as an inverted U (Kamijo, Nishihira, Hatta, Kaneda, Wasaka, et al., 2004; Kamijo et al., 2007) or inverted J (Kao, Westfall, Soneson, et al., 2017) shape during inhibitory control tasks, whereas such intensity-dependent effects on P3b amplitude were not observed following resistance exercise (Tsai, Wang, et al., 2014). Though four studies (19%) failed to show modulation of P3b or improved task performance following exercise, no negative effects were reported either (Popovich & Staines, 2015; Scanlon et al., 2017; Stroth et al., 2009; Yagi et al., 1999). Of these studies, the unchanged P3b from pre- to postexercise test was difficult to interpret because of the absence of a control group or condition (Popovich & Staines, 2015; Scanlon et al., 2017; Yagi et al., 1999) as well as the additional focus on P3b during exercise (Yagi et al., 1999). Further, one study (4.8%) observed null effects of acute physical activity on P3b (Stroth et al., 2009); however, such finding is confounded due to the assessment of P3b only at lateral electrode (rather than midline electrode) sites.

4 | DISCUSSION

4.1 | Summary of the search results

This systematic review summarizes evidence from studies investigating acute and chronic physical activity and cardiorespiratory fitness as they relate to the P3b-ERP component. The majority (93%) of studies included in this systematic review were deemed high quality based on criteria established in PRISMA (Moher et al., 2009), indicating a low risk of bias in the obtained findings. However, it should be noted that such a criteria rating pertains to study design and methodology but not necessarily task selection, physical activity/cardio-respiratory fitness assessment, or the method for collecting and analyzing the P3b. As such, detailed information regarding the characteristics of participants and physical activity interventions, as well as assessments of physical activity, physical fitness, and P3b were extracted for identifying potential modulators of the relationships of physical activity and cardio-respiratory fitness with the P3b-ERP.

4.2 | Physical activity and P3b amplitude

According to the present review, 56 (78.9%) of 71 reviewed studies (excluding Higuchi, Liu, Yuasa, Maeda, & Motohashi, 2000, on muscular fitness) showed associations of physical activity or cardiorespiratory fitness with P3b amplitude. Chronic physical activity engagement and superior cardiorespiratory fitness were associated with increased P3b amplitude (Chang, Chu, et al., 2017; Chang, Huang, et al., 2013; Dai et al., 2013; Fong et al., 2014; Hawkes et al., 2014; Hillman et al., 2004, 2005, 2006; Hillman, Buck, et al., 2009; Kamijo & Masaki, 2016; Luque-Casado et al., 2016; Polich & Lardon, 1997; Pontifex et al., 2009, 2011; Tsai, Chen, et al., 2014; Tsai & Wang, 2015; Tsai, Pan, et al., 2016; Wang & Tsai, 2016) or enhanced efficiency in the modulation of P3b amplitude in response to the upregulation of cognitive demands (Gajewski & Falkenstein, 2015; Kamijo & Takeda, 2010; Moore et al., 2014; Wu & Hillman, 2013) throughout the lifespan. Specifically, physical activity-related topographic shifts in P3b amplitude were found, suggesting compensatory brain activation in aging adults to support cognitive control and attention processes (Hillman et al., 2004, 2006; Huang et al., 2014; McDowell et al., 2003; a wider topographical distribution of P3b amplitude as shown in Figure 5b). Further, P3b amplitude differentiated physical activity and cardiorespiratory fitness-related changes in cognition among individuals with different characteristics (i.e., age, weight status, preferred physical activity type) (Chang, Chu, et al., 2017; Huang et al., 2014; Pontifex et al., 2009; Song et al., 2016; Tsai & Wang, 2015; Tsai, Wang, et al., 2016). Longitudinal studies designed to increase physical activity or cardiorespiratory fitness further demonstrated that chronic physical activity interventions resulted in increases in P3b amplitude (Chang, Tsai, et al., 2013; Hillman et al., 2014; Hsieh et al., 2017; Ludyga et al., 2018; Ozkaya et al., 2005; Tsai et al., 2017), and such effects were found to be positively associated with the dose of physical activity delivered through a moderate-to-vigorous intensity after-school physical activity intervention in children (Hillman et al., 2014). According to the available evidence to date, P3b amplitude may serve as a neuroelectric index, which affords the understanding of positive changes in attentional processes in relation to physical activity.

Similarly, even a single bout of light-to-moderate physical activity was associated with increased P3b amplitude following the cessation of the exercise bout (Chang, Alderman, et al., 2017; Chu et al., 2015; Drollette et al., 2014; Hillman et al., 2003; Hillman, Pontifex et al., 2009; Jain et al., 2014; Kamijo et al., 2009, 2007; Kamijo, Nishihira, Hatta, Kaneda, Wasaka, et al., 2004; Magnie et al., 2000; O'Leary et al., 2011; Pontifex et al., 2015, 2013; Scudder et al., 2012; Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016), with a few studies indicating that these effects may be moderated by cardiorespiratory fitness and cognitive capacity (Drollette et al., 2014; Tsai, Chen, et al., 2014; Tsai, Pan, et al., 2016). Similar exercise-induced increases in P3b amplitude were also observed after a long delay (i.e., 48 min) following vigorous exercise (Hillman et al., 2003); however, such effects might be attenuated or reversed when P3b was assessed only after a short delay following exercise at high intensities (Kamijo, Nishihira, Hatta, Kaneda, Wasaka, et al., 2004; Kamijo et al., 2007; Kao, Westfall, Soneson, et al., 2017). The findings for the modulation of P3b amplitude during exercise were much more equivocal, likely due to considerable heterogeneity in study methodology. Thus, the available evidence suggests that future research investigating the influence of exercise parameters such as intensity, duration, or dose on exercise-induced modulation of P3b amplitude both during and following bouts of physical activity is warranted.

4.3 | Physical activity and P3b latency

The association of physical activity with P3b latency was less consistent, as only 25 of 71 (35.2%) reviewed studies showed a significant relationship. This relationship was primarily characterized by negative associations of chronic physical activity engagement and cardio-respiratory fitness with P3b latency across age groups (Chang, Huang, et al., 2013; Hillman et al., 2005, 2006, 2002; Pontifex et al., 2011; Wang et al., 2016). Specifically, chronic physical activity and cardio-respiratory fitness may play a role in counteracting age-related slowing in processing speed (Dustman et al., 1990; Emmerson et al., 1989; Fong et al., 2014; Hillman et al., 2002, 2004). Such beneficial effects were further corroborated by findings of decreased P3b latency following chronic physical activity interventions designed for improving cardio-respiratory fitness during late adulthood and childhood, suggesting that the modulation of P3b latency may reflect the protective and facilitating effects of physical activity on processing speed in aging (Cetin et al., 2010; Chuang et al., 2015) and maturing (Chang, Tsai, et al., 2013; Hillman et al., 2014) populations, respectively. Negative associations between physical activity and P3b latency were also found following acute bouts of exercise (Drollette et al., 2014; Hillman et al., 2003; Jain et al., 2014; Kamijo et al., 2009; Kao, Westfall, Soneson, et al., 2017; Magnie et al., 2000; Pontifex et al., 2013), implying transient benefits on processing speed. During exercise, only two studies found effects on P3b latency with changes in divergent directions (Pontifex & Hillman, 2007; Yagi et al., 1999), making it challenging to conclude the relationship between exercise and concurrent processing speed.

Taken together, although one third of reviewed studies suggest that P3b latency may be associated with physical activity, the consistency of such an effect appears low because null associations were found across 46 (64.8%) cross-sectional and intervention studies. The less frequent observation of relationships between physical activity and P3b latency may be the result of quantifying P3b latency using the peak measure, which is thought to be less robust against noise (Luck, 2014). Thus, future research should investigate P3b latency using other quantification methods (i.e., fractional peak/area latency) that have been shown to be more resistant to unwanted variances when measuring latency of a larger ERP component such as P3b (Luck, 2014).

For the latency measures, the peak latency measure will likely not be robust against increases in noise because noise will distort the latency of the true ERP peak; the noise will be superimposed on the true peak thus altering the minimum or maximum amplitude of the peak and subsequently biasing the peak latency measure.

4.4 | Physical activity and behavior

Although the focus of the current review was on the P3b, the consideration of behavioral outcomes during neuroelectric assessments is complementary to the interpretation of changes in the P3b-ERP component. In our review, the majority of studies coupled P3b findings with behavioral outcomes (Figure 4); however, specific relationships between physical activity-related changes in P3b and behavior were less frequently investigated. That is, although increased P3b amplitude and/or decreased P3b latency were frequently paralleled by improved behavioral performance, limited evidence exists to determine the potential mechanistic link between the physical activity-related changes in P3b and behavioral performance. To date, only two studies demonstrated associations of P3b with task performance in relation to physical activity and cardio-respiratory fitness (Ludyga et al., 2018; Wang et al., 2016), providing preliminary evidence to support the notion that P3b may play a role in the relationship between physical activity, cardio-respiratory fitness, and cognitive performance.

However, some studies showed physical activity-related modulation of P3b activation in support of cognition without changes in behavioral performance during simple discrimination tasks (e.g., oddball or choice RT tasks, Cetin et al., 2010; Dustman et al., 1990; Emmerson et al., 1989; Hillman et al., 2002; McDowell et al., 2003; Ozkaya et al., 2005; Polich & Lardon, 1997; Pontifex et al., 2015; Zink et al., 2016), suggesting that P3b may be a more sensitive measure for detecting the positive effect of physical activity on simple discrimination processing. In contrast, two studies showed physical activity-related benefits to RT without accompanying modulations of P3b (Bullock et al., 2015; Getzmann et al., 2013). Instead, the improved behavioral performance observed in these studies was paralleled with decreased latency (Bullock et al., 2015) and amplitude (Getzmann et al., 2013) of P3a, a subcomponent of P3 complex elicited by infrequent distractors embedded in a two-stimulus discrimination task. P3a reflects a neuroelectrical mechanism that can be dissociated from P3b, as its neural origin has been linked to the frontal regions and its functional significance has been related to attentional orienting or involuntary shifts to the changes in the environment (Polich, 2007). Accordingly, physical activity may be associated with early shifts in attentional orienting when their influence on subsequent updating of working memory is not observed. Further, a few studies showed that physical activity and cardiorespiratory fitness were associated with improved task performance but patterns of P3b indicative of suboptimal cognitive operations (i.e., decreased P3b amplitude, increasd P3b latency; Chu et al., 2015; Moore et al., 2014; Kamijo & Takeda, 2009; Wu & Hillman, 2013). These unexpected associations were thought to be the result of the use of unique P3b assessment or analytical approach. Taken together, although these existing findings in uncoupled P3b and behavioral indices in relation to physical activity may be attributed to discrepancies in methodologies across studies, they also suggest that physical activity may affect P3b and behavior through different mechanisms.

4.5 | Potential mechanisms underlying physical activity effects on P3b

Although several mechanisms including neurogenesis, angiogenesis, neural plasticity, as well as acute changes in central nervous system activation such as neurotransmission and cerebral metabolism have been proposed to account for the chronic and acute effects of physical activity on cognition (for a review, see McMorris et al., 2016; Voss et al., 2013), the direct mechanisms underlying the associations between physical activity and P3b remain unclear. In Polich's (2007) seminal review, P3b was proposed as a neuroelectric marker of memory updating and storage processes following the reorienting of attentional focus. In this theoretical framework, P3b is the dominant positive brain potential that is the neuroelectric consequence of facilitating memory processes via inhibiting task-irrelevant brain activation (Polich, 2012). This hypothesis is well supported by the majority of research showing the associations of physical activity and cardio-respiratory fitness with P3b during inhibition tasks, especially in children and older adults who are experiencing rapid age-related development in brain structure and function related to inhibitory control processes (Cabeza, Anderson, Locantore, & McIntosh, 2002; Coxon, Van Impe, Wenderoth, & Swinnen, 2012; Durston et al., 2002; Sweeney, Rosano, Berman, & Luna, 2001; Tamm, Menon, & Reiss, 2002; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Such associations of physical activity with P3b and neuroinhibition may be attributed to the changes in arousal, a blended state of physiological and psychological activation that is regulated by reticular activating system (Steriade, 1996). As part of this system, it has been hypothesized that exercise-induced increases in NE (McMorris et al., 2016) modulate arousal levels that are responsible for improved attention and vigilance (Kinomura, Larsson, Gulyas, & Roland, 1996) as well as modulation of higher-order cognitive functioning (Berridge & Waterhouse, 2003). Specifically, research has proposed that the LC-NE system modulates the P3b to titrate attentional processes to meet environmental demands (Chmielewski, Mückschel, Ziemssen, & Beste, 2017; Nieuwenhuis et al., 2005; Nieuwenhuis, De Geus, & Aston-Jones, 2011), with intermediate levels of LC-NE activation associated with increases in P3b amplitude (Murphy et al., 2011). Such findings are in agreement with increased P3b amplitude following acute bouts of exercise at moderate compared to low and high intensities (Kamijo et al., 2007; Kao, Westfall, Soneson, et al., 2017), suggesting that the tonic LC-NE activation underlying a moderate arousal level may mediate neuroinhibition to support attentional processes required to perform the cognitive task. The role of the LC-NE system in P3b modulation in relation to physical activity may go beyond the acute bout, as the accumulation of physical activity and cardio-respiratory fitness are associated with structural and functional adaptations in the central nervous system (Voss et al., 2013), which may further include chronic changes in LC-NE activation (Polich, 2012; Polich & Kok, 1995). Further, enhancements in structural and functional integrity of medial temporal lobe associated with chronic physical activity and cardio-respiratory fitness may contribute to the changes in P3b activation, as the size of the hippocampus and temporal/parietal activation were found to be associated with P3b (Polich, 2007, 2012). However, limited evidence exists to directly investigate the role of LC-NE and hippocampal networks in the associations of physical activity and cardio-respiratory fitness on P3b. Clearly, further research is needed to empirically determine these potential mechanisms.

4.6 | Limitation and future directions

Although the findings from this review suggest that physical activity engagement and cardio-respiratory fitness have beneficial associations with brain function, as indexed by modulation of the P3b component, limitations exist in the literature.

4.6.1 | Assessment of physical activity and physical fitness

The findings from cross-sectional studies were limited due to the collected physical activity and physical fitness outcomes. The inconsistent operational definitions or heterogeneity in assessments of cardio-respiratory fitness (i.e., 13 studies using a direct measure of VO_{2max} or VO_{2peak} vs. 7 studies using indirect estimate such as PACER or YMCA submaximal exercise protocols) and physical activity (i.e., various versions of self-reported questionnaires) may have contributed to some of the discrepant findings across studies. Specifically, none of the reviewed studies used objective measures of physical activity, such as accelerometers to examine the associations between chronic physical activity and P3b. Given that self-reported physical activity affords limited ability to characterize the patterns of physical activity such as the intensity, duration, and frequency of physical activity (Troiano et al., 2008), the findings from the existing literature can only provide generalized support for a relationship between chronic physical activity and P3b. That is, a dearth of literature regarding how the characteristics of the physical activity exposure may relate to P3b cannot be determined at this time.

Despite accumulating evidence indicating the negative impact of sedentary behavior on cognition (Carson et al., 2015; Falck, Davis, & Liu-Ambrose, 2017), our search did not find any qualified studies for the current review, suggesting the necessity of determining the associations of this unhealthy behavior with P3b. Moreover, although emerging evidence has demonstrated the beneficial associations of muscular (Firth et al., 2018; Kao, Westfall, Parks, et al., 2017) and motor (Aadland et al., 2017; Voelcker-Rehage et al., 2010) fitness with behavioral performance using a variety of cognitive tasks, research on the relationship between physical fitness and P3b has been limited to the cardio-respiratory domain. To date, only one study has investigated muscular fitness using a measure of hand grip strength (Higuchi et al., 2000). Accordingly, future research is needed to provide more precise assessments of physical activity patterns and comprehensive measures of multiple domains of physical fitness to better understand the nature of the relationship between physical activity and physical fitness with neural processes captured by the P3b-ERP component.

4.6.2 | Assessment of P3b

The findings of this review revealed that acute and chronic physical activity interventions were related to changes in P3b activation during cognitive tasks; however, none of the existing studies conducted follow-up assessments to determine how long physical activity-induced changes in P3b were sustained. Further, no studies conducted multiple assessments of P3b throughout the course of chronic physical activity interventions to determine the minimal physical activity dose for inducing changes in the P3b-ERP component. Understanding such dynamics over the period of a physical activity intervention is of great importance, as it could provide empirical evidence to characterize the temporal progress of functional adaptations in the brain in response to physical activity, which in turn may guide the development of physical activity interventions targeting cognitive and brain health. Accordingly, future research should aim to characterize changes in P3b across, as well as maintenance of such changes following, physical activity interventions.

Although convergent findings indicated the beneficial associations of cardio-respiratory fitness and physical activity with the P3b-ERP, the domains of cognitive function and the tasks used to assess P3b vary considerably in the literature. Cognitive control can be parsed into three independent, yet inter-related, components, including inhibitory control, working memory, and cognitive flexibility (Miyake & Friedman, 2012). The majority of studies focused on the relationship of physical activity and cardio-respiratory fitness with P3b during inhibitory control tasks (see Table 4), with working memory and cognitive flexibility less studied. Further, given that most studies included only one aspect of cognitive control in relation to physical activity and cardio-respiratory fitness, it is difficult to conclude whether different domains of cognitive control have differential sensitivities to physical activity and cardio-respiratory fitness. Thus, future research should determine the specificity of the association between physical activity and cardio-respiratory fitness with P3b across subdomains of cognitive control.

Even when P3b was assessed within each subdomain of cognitive control and attention, considerable variability in methodology existed. In most cases, increased amplitude and decreased latency of P3b are indicative of enhanced cognitive processes, but exceptions exist due to the differential nature of each task. For instance, increased P3b amplitude during an attentional blink task may indicate ineffective attentional resources allocation to achieve the task goals (Wu & Hillman, 2013). A larger increase in P3b latency from negative priming to a nonpriming task condition may indicate more effective top-down attentional control (Kamijo & Takeda, 2009). When evaluating findings across studies, differences in the procedures for measuring P3b amplitude and latency may create challenges, which can be exemplified by the different patterns of associations between chronic physical activity and P3b amplitude due to the use of peak and mean measurement (McDowell et al., 2003). Indeed, a large proportion of the reviewed studies did not report the minimum numbers of artifact-free EEG segments for obtaining P3b measures, making the signal-to-noise ratio of the observed P3b-ERP unclear (Keil et al., 2014). Moreover, most of the null findings in the literature base were associated with at least some aspects of methodology that deviated from the majority of the literature, such as the lack of a control group or condition (Popovich & Staines, 2015; Scanlon et al., 2017; Yagi et al., 1999), exposure of novel environments or equipment (Torbeyns et al., 2016; Vogt et al., 2015; Zink et al., 2016), hybrid cognitive paradigms (Berchicci et al., 2014; Bullock et al., 2015; Getzmann et al., 2013; Pontifex et al., 2009; Stroth et al., 2009; Zink et al., 2016), or a lesser used approach for evaluating the P3b component (Hawkes et al., 2014; Moore et al., 2013; Scisco et al., 2008; Stroth et al., 2009). For example, the exclusion of midline electrodes from analysis may substantially reduce the effect of physical activity or cardio-respiratory fitness on the P3b (Stroth et al., 2009). Thus, to minimize the potential for assessment-related variance to obscure the understanding of physical activity and cardio-respiratory fitness effects on P3b, future research should focus on building out of standard methodological approaches (Keil et al., 2014).

4.7 | Conclusions

The existing body of evidence suggests that cardio-respiratory fitness and physical activity are positively associated with changes in the P3b potential, suggesting modulations of neuroinhibition underlying more effective attentional resource allocation and, to a lesser extent, faster processing speed. However, these associations may be dependent on the assessment of physical activity, fitness, P3b, individual differences in the participants' population, and exercise parameters. Nonetheless, our findings suggest that P3b may serve as a useful biomarker to elucidate the acute and chronic effects of physical activity on adaptations of neural electrophysiology beyond the overt changes in behavioral performance during cognitive task engagement. Future research in the field of physical activity and cognition are needed to advance our understanding of the mechanism underlying the physical activity-P3b relationship and the potential application of physical activity for enhancing cognitive and brain health.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1
Table S1
Table S2
Table S3

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