Psychology of Sport & Exercise 40 (2019) 1–22

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

Review

# A primer on investigating the after effects of acute bouts of physical activity on cognition

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ARTICLE INFO

*Keywords:*
Physical activity
Cognition
Exercise

ABSTRACT

An emerging body of evidence has begun to document the beneficial after effects of single bouts — or doses — of physical activity for cognition. This article highlights a selection of common themes and critical delimitations that investigators new to this area of research as well as those currently working in the field may find relevant for advancing research in this area. The intent of this article is to provide a stimulus for future investigations to enhance not only the breadth and depth of the evidence, but also the experimental rigor. In doing so, a number of fundamental considerations are discussed including the aspects of cognition predominantly focused upon to date, issues related to the dose of the physical activity (i.e., how long the after effects persist, what characteristics of the dose may maximize the cognitive after effects), potential moderating variables, as well as potential underlying mechanisms. Additionally, discussion is provided regarding methodological considerations for future investigations including implications of the experimental design, control conditions, and cognitive assessment utilized, as well as statistical and reporting considerations to facilitate transparency. By calling attention to these areas, the hope is that future research may advance our understanding of the underlying mechanisms, theoretical development, and clinical relevance of the cognitive after effects of these single doses of physical activity.

A growing body of research has investigated the relationship between physical activity and cognition with an eye towards understanding how societal trends for sedentary behavior might negatively impact not only physical health, but cognitive health and function as well. Indeed, both the Scientific Report of the 2018 Physical Activity Guidelines Advisory Committee (2018) and the Canadian Physical Activity Report Card (ParticipACTION, 2018) highlight the importance of physical activity for sustaining optimal levels of brain health. Although the vast majority of research in this area has focused on chronic physical activity engagement as it relates to the brain and cognition, a number of investigations have extended this work with the goal of understanding the influence of a single bout — or dose — of physical activity on cognition. That is, much like a dose of medication is taken, physical activity is engaged in through single bouts. While the extant evidence-base generally supports a positive association between acute bouts of physical activity and cognition, there is still much work to be done in this area. The intent of this review is to highlight a selection of common themes and critical delimitations that investigators new to this area of research — as well as those currently working in the field — may find relevant for advancing research investigating the after effects of these single bouts of physical activity on cognition by integrating the domains of kinesiology, cognitive psychology, and neuroscience.

As research in the area of acute physical activity and cognition progresses, it is important that we dissociate investigations assessing changes in cognition *following* a bout of physical activity — which are the focus of this review — from those studies assessing changes in cognition *during* physical activity. Indeed, investigations evaluating changes in cognition during physical activity are conceptually different given that they necessarily entail a dual-task environment. Similarly, understanding how facilitations in cognition resulting from acute physical activity transition to more chronic effects is a particularly interesting area of research. However, it is inappropriate to cluster those studies assessing the effects of a single bout of physical activity together with those measuring the effects of months or years' worth of habitual physical activity as these are substantially different constructs of interest. Further, although the field has largely utilized the phrase 'acute exercise', the characteristics of the activities utilized within the extant literature are more appropriately clustered within the umbrella term of

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https://doi.org/10.1016/j.psychsport.2018.08.015
Received 28 March 2018; Received in revised form 20 July 2018; Accepted 29 August 2018
Available online 11 September 2018

'physical activity' rather than 'exercise'. Indeed, while investigations in this area largely use activities which require energy expenditure above and beyond resting levels — defined as physical activity; those activities are not implemented in a planned, structured manner with the intent of the activity improving or maintaining one or more components of physical fitness — which would be construed of as exercise (American College of Sports Medicine, 2018). Accordingly, the use of the term 'physical activity' provides a more conceptually appropriate descriptor.

Within those investigations assessing changes in cognition following a bout of physical activity, to date, meta-analytic reviews generally support the conclusion that there is a beneficial after effect of single bouts of physical activity on cognition with effect size estimates of 0.1 (Chang, Labban, Gapin, & Etnier, 2012), 0.16 (Etnier, Salazar, Landers, & Petruzzello, 1997), and 0.2 (Lambourne & Tomporowski, 2010). Although these effects are small, it is important to note that the literature in this area varies greatly in the characteristics of physical activity and the methodological strength of the work, both of which appear to influence the extent to which cognition is impacted following a single bout of physical activity (Chang, Labban, et al., 2012; Etnier et al., 1997; Lambourne & Tomporowski, 2010). Accordingly, the aim of this review is to provide a resource for investigators new to this area of research as well as those currently working in the field to better understand some of the critical characteristics of the existing literature base. This approach aims to highlight those aspects of cognition that have been predominantly focused upon, in addition to providing some discussion of the persistence of these cognitive enhancements, issues and considerations for the dose of the physical activity, potential moderating variables, and mechanisms that may explain the facilitative acute effects of physical activity on cognition. Additionally, discussion is provided regarding methodological considerations for future investigations including implications of the experimental design, control conditions, and cognitive assessments utilized, as well as statistical and reporting considerations to facilitate transparency.

## 1. Extant research in this area

In light of this purpose, the present review examined the published literature investigating the cognitive after effects of a single bout of physical activity. Studies were identified from previous reviews and meta-analyses (Chang, Labban, et al., 2012; Etnier et al., 1997; Lambourne & Tomporowski, 2010; Ludyga, Gerber, Brand, Holsboer-Trachsler, & Pühse, 2016; Tomporowski, 2003a, 2003b; Tomporowski & Ellis, 1986) as well as examination of reference sections from published studies in this area for any study published in 2017 or earlier. Additionally, searches of Google Scholar were conducted using search terms to acquire studies. A broad search strategy was used to return as many results as possible: searches used the logical operator "OR" between exercise-related terms (i.e., "exercise", "physical activity", "physical exercise") and the logical operator "AND" between the exercise-related terms and the cognition search modifier cogniti* (i.e., "cognition", "cognitive"). Studies were included if they were published prior to 2018 and examined the after effects of single bouts of physical activity on cognition. Physical activity was defined based upon American College of Sports Medicine criteria (2018) and cognition was defined consistent with the approach used by Chang, Liu, Yu, and Lee (2012). Unpublished studies and non-peer reviewed publications were excluded from this review. This approach resulted in a total of 172 studies that were identified as investigating the cognitive after effects of an acute bout of physical activity published prior to 2018. Each of these studies were independently coded by two of the study authors (AM, MC) to classify the aspect(s) of cognition focused upon, timing of task administration following physical activity, intensity, duration, and type of activity performed, subject population, experimental design, type of control, and sample size. Across all ratings, the independent coders exhibited a high degree of consistency (Fleiss's kappa = 0.88, 93.4%

**Table 1**
Categorization of cognitive tasks and approaches.

| |
|---|
| **Attention** |
| Attention Network Test (ANT) - Alerting/Orienting |
| d2 Test of Attention |
| Feature match and polygons |
| Odd-One-Out |
| Oddball |
| Paced Auditory Serial Addition Test (PASAT) |
| Psychomotor Vigilance Task (PVT) |
| Spatial Attention/Posner Spatial Attention/Spatial Search and Spatial Slider |
| Sustained Attention to Response Task (SART)/Picture Deletion Task for Preschoolers (PDTP) |
| Visual Search Task |
| Woodcock-Johnson Test of Concentration |
| **Cognitive Control** |
| *Unitary Construct* |
| Mental Loading Task |
| Tower of Hanoi |
| Tower of London |
| Wisconsin Card Sorting Task |
| *Inhibition* |
| Attention Network Test (ANT) - Executive |
| Flanker Task |
| Go/No-Go Task |
| Incompatible Reaction Time |
| Simon Task |
| Stop Signal Task |
| Stroop Task |
| *Working Memory* |
| Brown Peterson/Brown Poulton |
| Corsi Blocks |
| Digit Span (Backward) |
| Digit Span (Forward) |
| N-Back |
| Operation Span |
| Random Number Generation |
| Reading Span |
| Spatial Span |
| Sternberg Task |
| Verbal Running Span |
| Verbal Working Memory (Auditory Verbal Learning or California Verbal Learning Test) |
| *Cognitive Flexibility* |
| Alternate Uses Task |
| Local Global Task |
| Task-Switching |
| Trail-Making-Test |
| **Information Processing** |
| Anticipation/Coincident Timing Task |
| Critical Flicker Fusion |
| Digit Symbol Substitution |
| Math Computation |
| Math Problem Solving |
| Symbol Digit Modalities Test (SDMT) |
| Visual Field |
| **Intelligence & Achievement Tests** |
| Eysenck's IQ: Numerical ability |
| Eysenck's IQ: Verbal |
| Eysenck's IQ: Visuospatial |
| Grammatical Reasoning |
| Kaufman Brief Intelligence (KBIT) |
| Nonverbal Matrices |
| Raven's Progressive Matrices |
| Remote and Obvious Consequences |
| Verbal Fluency/Word Fluency |

(*continued on next page*)

**Table 1** (*continued*)

| |
|---|
| Weschler Adult Intelligence Scale (WAIS) |
| Weschler Test of Adult Reading (WTAR) |
| Wide Range Achievement Test (WRAT) |
| **Memory** |
| Delayed Match-to-Sample |
| Delayed Recall |
| Free Recall |
| Hopkins Verbal Learning Test (Revised) |
| Matching Familiar Figures Task |
| Modified Benton Visual Retention Test |
| New York University Paragraphs for Immediate and Delayed Recall (a subtest of the Guild Memory Test) |
| Nonsense Syllables |
| Novel Object Recognition Memory Task |
| Paired Associate |
| Rey Auditory Verbal Learning Test (RAVLT) |
| Sequential Memory |
| **Motor Speed & Learning** |
| Choice Reaction Time |
| Continuous Tracking Task |
| Finger Tapping |
| Simple Reaction Time |
| **Neuroimaging** |
| Electroencephalography (EEG) |
| Event-Related Potential (ERP) |
| Functional Near-Infrared Spectroscopy (fNIRS) |
| Functional Magnetic Resonance Imaging (fMRI) |

agreement); in instances where there was disagreement between coders, a third coder (MP) joined the discussion and a consensus was reached as to the correct coding. To facilitate greater transparency, the complete listing of each identified study and its respective coding is provided in the Supplemental Materials.

### 1.1. What aspects of cognition have been investigated?

In order to provide an over-arching perspective as to those aspects of cognition the field has focused upon, it was necessary to classify each study within the literature with regard to the domain(s) of cognition of interest. It is important to point out that such delineations are somewhat arbitrary as some cognitive assessments may rely upon or provide an index of multiple cognitive domains. Furthermore, there is continued debate as to how best to differentiate cognitive assessments; for consistency with the extant literature base, the present review adapted the cognitive classification scheme used by Chang, Liu, et al. (2012). Thus, cognitive assessments were categorized as examining attention, cognitive control, information processing, intelligence and achievement tests, memory, or motor speed and learning (see Table 1 for a breakdown of those assessments included within each domain of cognition). Additionally, as neuroimaging/psychophysiological measures provide an additional perspective regarding cognitive operations, studies were also coded with regard to if they utilized neuroimaging approaches. To facilitate discussion of these cognitive domains, effect size estimates were extracted as Cohen's d from homogenous studies when available.

Similar to the chronic physical activity literature, much of the early work in this area focused on the influence of acute bouts of physical activity on simple motor speed/learning, information processing, and attention. This focus was built upon theoretical frameworks of the relationship between physical arousal and behavior such as the inverted-U theory, drive theory (Spence & Spence, 1966), and cue-utilization theory (Easterbrook, 1959). At that time, these theories had largely been applied to the domains of anxiety and motor skill behavior (Tomporowski & Ellis, 1986), but the research began examining the extent to which bouts of physical activity might induce changes in cognitive processes. Although much of this work was predominantly focused on changes in simple motor speed/learning, information processing, and attention occurring during the activity, physical activity also appears to result in transient enhancements following the cessation of the activity. Specifically, investigations of physical activity-induced changes in motor speed have generally relied upon simple and choice reaction time tasks and have observed enhancements in the speed of responding following an acute bout of physical activity (effect sizes ranging from Cohen's d of 0.2–0.5; Córdova, Silva, Moraes, Simões, & Nóbrega, 2009; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Kashihara & Nakahara, 2005; Patil, Patkar, & Patkar, 2017). Similarly, investigations of selective and sustained attention have generally observed facilitations in the ability to focus and maintain attention following acute bouts of physical activity (effect sizes ranging from 0.1 to 0.69; Budde et al., 2012; Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro, & Tidow, 2008; De Marco et al., 2015; Hsieh, Chang, Fang, & Hung, 2016; Loprinzi & Kane, 2015; Scudder, Drollette, Pontifex, & Hillman, 2012; van den Berg et al., 2016; Wohlwend, Olsen, Håberg, & Palmer, 2017). Information processing, alternatively, appears to exhibit a more inconsistent relationship with physical activity; with some investigations observing enhanced performance on digit symbol substitution tasks immediately following a bout of physical activity (effect sizes ranging from 0.2 to 0.5; Emery, Honn, Frid, Lebowitz, & Diaz, 2001; Molloy, Beerschoten, Borrie, Crilly, & Cape, 1988), whereas others have failed to observe any effect following physical activity (Cooper et al., 2016; Stones & Dawe, 1993). Consonant with such assertions, meta-analytic findings have generally observed small effect sizes of acute bouts of physical activity across these aspects of cognition (Chang, Labban, et al., 2012).

Part of the conceptual justification for focusing on what have been termed "low level" cognitive processes (such as simple motor speed/learning or information processing tasks) was the idea that from a systems perspective: 'high-level' cognitive operations (such as cognitive control) should be relatively invariant and robust to systemic changes, to protect the integrity of the organism. Thus, it would be more likely that if single bouts of physical activity were to influence the system it would be observed within 'low-level' processes. However, cognitive control is not just an *a priori* static state but rather is dynamic and regulative in nature (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Therefore, cognitive control operations might also change in response to systemic shifts in the organism. Following the seminal meta-analysis of Colcombe and Kramer (2003) indicating that chronic physical activity interventions exhibited disproportionately greater influence over cognitive control operations, the acute physical activity literature largely shifted to focus upon this domain of cognition. As depicted in Fig. 1a, although there has been an exponential increase in the number of studies investigating the influence of a single bout of physical activity on cognition over the last decade, the vast majority of these new studies — and 60% of the overall literature — have focused upon cognitive control operations.

For clarification, the term cognitive control (also known as executive function) refers to a class of cognitive operations that facilitate goal-directed interactions with the environment through problem solving, resisting temptations or distractions, and maintaining control over actions (Meyer & Kieras, 1997; Norman & Shallice, 1986; but see Jurado & Rosselli, 2007 for further discussion of this construct). An important distinction is that although early perspectives on the construct of cognitive control included a wide assortment of cognitive processes under this umbrella term, modern theoretical perspectives of cognitive control suggest that this class of cognition is comprised of the processes of inhibition, working memory (also referred to as updating), and cognitive flexibility (also referred to as shifting; Davidson, Amso,

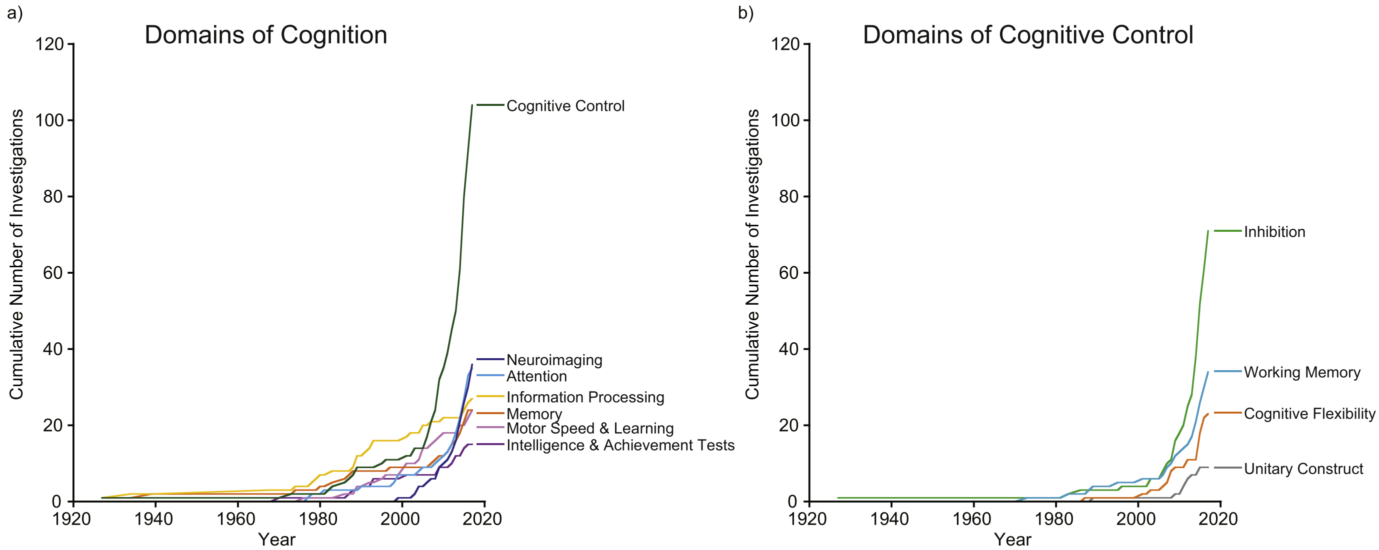


**Fig. 1.** Illustration depicting the cumulative number of investigations assessing each domain of cognition (a) and the cumulative number of investigations assessing each domain of cognitive control (b). Note that publications assessing several domains of cognition are counted within each respective domain, thus the total number of publications assessing the cognitive after effects of acute physical activity is less than the summation of publications depicted across all domains of cognition.

Anderson, & Diamond, 2006; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Factor analysis of performance across a battery of tasks that conceptually fit into classical cognitive control domains support a unitary model of cognitive control in children 2–6 years old (Wiebe, Espy, & Charak, 2008). Over the course of maturation, these cognitive control processes are believed to become more functionally distinct, in parallel to the maturation of neural networks and regions thought to be vital for supporting cognitive control operations including the anterior cingulate cortex, prefrontal cortex, basal ganglia, superior frontal sulcus, and insular and parietal cortices (Bunge & Crone, 2009; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Travis, 1998). To appropriately reflect these subdomains of cognitive control in this review, cognitive assessments providing an index of cognitive control were additionally classified into those tasks providing an index of a unitary — or global — construct and those tasks indexing inhibition, working memory, or cognitive flexibility specifically (see Table 1). Using this approach, the exponential increase in the number of studies investigating the influence of a single bout of physical activity on cognitive control over the last decade has largely been a function of new studies focusing on inhibitory aspects of cognitive control (see Fig. 1b and Fig. 2).

Indeed, more research has been conducted investigating inhibitory aspects of cognitive control than any other domain of cognition, with inhibition being investigated by 41% of the published studies in the literature. In particular, two assessments of inhibitory control exhibit marked prominence in the literature: the Stroop task and the Flanker task. Both of these paradigms require participants to monitor and suppress conflict induced by task-irrelevant information in order to execute the correct behavior. During the Stroop task, participants are asked to indicate the color of ink in which a string of letters are presented (i.e., 'XXX' presented in red ink). Given the pre-potent tendency to read, when the string of letters forms a color-word (i.e., 'BLUE' presented in red ink) the participants must inhibit that reading tendency in order to respond to the color of the ink. The Flanker task asks participants to respond based upon a centrally presented stimulus nested within an array of flanking stimuli (i.e., '< < < < <'). When the flanking stimuli are mapped to opposing stimulus-response associations (i.e., '> > < > >'), the participant must inhibit the perceptually-induced response conflict in order to respond to the target

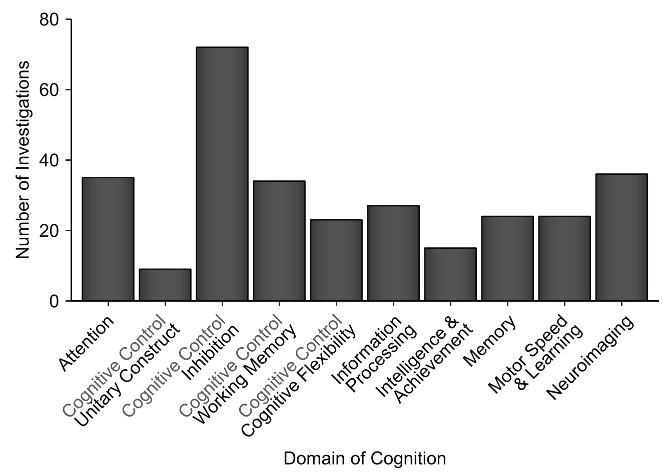


**Fig. 2.** Illustration of the number of investigations assessing each domain of cognition.

stimulus. Regardless of the task, investigations assessing the effect of an acute bout of physical activity on inhibition have generally observed enhanced interference control following physical activity engagement, with Stroop effect sizes ranging from 0.2 to 1.16 (Barella, Etnier, & Chang, 2010; Byun et al., 2014; Chang & Etnier, 2009b, 2009a; Chang, Liu, Yu, & Lee, 2012; Chang, Tsai, Huang, Wang, & Chu, 2014; Hogervorst et al., 1996; Lichtman & Poser, 1983; Peruyero, Zapata, Pastor, & Cervelló, 2017; Yanagisawa et al., 2010), and Flanker effect sizes ranging from 0.2 to 0.95 (Chen, Yan, Yin, Pan, & Chang, 2014; Hillman et al., 2009; Hillman, Snook, & Jerome, 2003; Jäger, Schmidt, Conzelmann, & Roebers, 2014; Ludyga et al., 2016; Sandroff, Hillman, Benedict, & Motl, 2016; Weng, Pierce, Darling, & Voss, 2015).

An emerging body of research has begun utilizing neuroimaging/psychophysiological measures (such as electroencephalography, event-related brain potentials, functional near-infrared spectroscopy, and functional magnetic resonance imaging) to assess the after effects of single bouts of physical activity. The benefit of these approaches is that they enable the acquisition of information regarding how neural structures and/or processes respond in a way that may not always be directly observable through assessing behavioral outcomes alone. Indeed, classically, these neuroimaging/psychophysiological measures have been used to provide insights into the psychological 'black box' occurring between inputting a stimulus and obtaining a response (Andreassi, 2007). With the growing utilization of these measures, a key question is to what extent changes in neural processes/structures should be viewed as mechanisms potentially underlying alterations in behavior or if these neural measures should be construed as related, yet distinct, outcome measures. Although the classical 'black box' model necessarily infers some degree of causality — the 'black box' processes the stimulus and outputs a response; it is important to acknowledge that our present methods of neuroimaging/psychophysiological inquiry provide a very limited insight into this psychological 'black box'. In some contexts, these insights may indeed be occurring in a serial process between stimulus encoding and response production and therefore would exhibit stronger associations with behavioral outcomes. Conversely, in other contexts, these insights may reflect regulatory or parallel processes that exhibit less direct or more inconsistent relations with behavioral outcomes (Sander & Zhou, 2016). Thus, caution is warranted in making mechanistic attributions from neuroimaging/psychophysiological measures.

Prior studies have provided evidence to indicate that single bouts of physical activity enhance a number of neural processes and structures. One measure that has received a great deal of focus is the P3 event-related brain potential which provides insights into the allocation of attentional resources during stimulus engagement. These investigations generally observe moderate-to-large effects (ranging from 0.6 to 1.9) for enhancements following single bouts of physical activity relative to following control (Hillman et al., 2003, 2009; Kamijo et al., 2009; Kamijo, Nishihira, Higashiura, & Kuroiwa, 2007; O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011; Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). Other neuroimaging approaches have attempted to gain insight into neural regions that exhibit greater activation following a single bout of physical activity. Specifically, investigations utilizing functional near-infrared spectroscopy in response to the Stroop task have observed greater cortical activation following physical activity in the left dorsolateral prefrontal cortex (effect sizes ranging from 1.2 to 1.3; Byun et al., 2014; Yanagisawa et al., 2010) and the frontopolar area (effect sizes ranging from 0.8 to 1.2; Byun et al., 2014; Hyodo et al., 2012). Although preliminary, using functional magnetic resonance imaging, Li et al. (2014) have observed greater activation of the right middle frontal gyrus, right lingual gyrus, and left fusiform gyrus and reductions in activation in the anterior cingulate cortex, left inferior frontal gyrus, and right paracentral lobule following physical activity relative to control (effect sizes ranging from 1.2 to 1.5). Accordingly, these neuroimaging findings would appear to align with the behavioral literature that has observed physical activity-induced enhancements in aspects of 'high-level' cognitive operations subserved by these neural regions.

Collectively, given the predominant focus upon only a few aspects of cognition common within the literature to-date, we still have a relatively immature understanding of the extent to which other aspects of cognition are influenced by or are immune to the effects of bouts of physical activity. While meta-analytic findings generally support the conclusion that there is a net positive influence following a single bout of physical activity across all aspects of cognition (Chang, Labban, et al., 2012; Etnier et al., 1997; Lambourne & Tomporowski, 2010; Ludyga et al., 2016), such observations are necessarily drawn from the aspects of cognition that have been assessed to date. Thus, we cannot rule out that there may be aspects of cognition that are not influenced by bouts of physical activity.

### 1.2. How long do these effects persist?

Given the potential utility of research in this area, it is vital that we gain an understanding of the persistence of acute physical activity-induced facilitations in cognition and the factors that serve to extend or diminish its effects. In order to provide an over-arching perspective of this issue, we characterized the timing following the physical activity bout in which the cognitive assessment was given. Despite the critical importance of understanding the persistence of these acute physical activity effects, 10% of the literature has failed to provide sufficient information from which to determine when the cognitive assessments were administered. Further, although meta-analytic reviews have suggested that the greatest enhancements occur within a 15 min period following activity (Chang, Labban, et al., 2012; Lambourne & Tomporowski, 2010), a critical impediment to this conclusion is that the vast majority of the published literature (41%) has examined cognition immediately following the cessation of physical activity, with only 17% of studies investigating time periods beyond 30 min (see Fig. 3). Given such constraints, it would appear premature to make strong claims regarding the persistence of acute physical activity-induced enhancements in cognition.

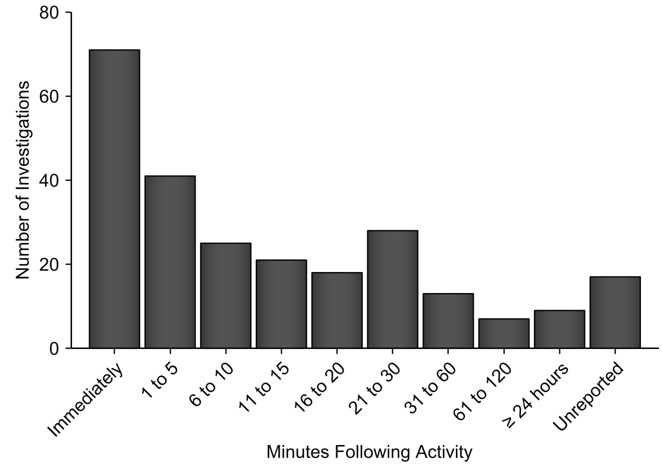


**Fig. 3.** Illustration of the number of investigations assessing cognition within each specified period after the physical activity condition.

However, it is also important to acknowledge that the standard method of reporting the timing of the start of the cognitive assessment relative to the cessation of activity is likely sub-optimal for understanding the persistence of the effects of physical activity. That is, the total time necessary to complete a cognitive assessment is widely variable. The difficulty, thus, lies in the consideration of whether two studies that both start assessing cognition 10 min after physical activity should be clustered together if one study used a task that takes 1 min to complete while the other study used a task that takes 10 min to complete. If 15 min is indeed some critical window following physical activity, then the first study might show enhancements whereas the second might not — simply because a sizable portion of the task occurs beyond this critical window. Pragmatically then, it may be more appropriate that investigators begin reporting — or report in a more transparent fashion — the total duration of the cognitive assessment alongside the timing of the assessment following cessation of physical activity. Such reporting would better allow for the characterization of the post-activity effects and highlight differences between studies relative to the overall burden placed upon participants. That is, participant fatigue may also play a mediating role in the persistence of these acute physical activity effects as investigators task participants with completing multiple consecutive cognitive assessments. Such approaches would therefore beg the question of to what degree diminished effects are functions of the decaying effects of acute physical activity or participant burden/fatigue.

In order to substantially advance the literature in this area, it is also necessary for future investigations to branch out and investigate longer periods following the cessation of activity to determine the point at which these after effects are diminished or if there is an oscillatory pattern of responses such that effects ebb-and-flow in concert with their

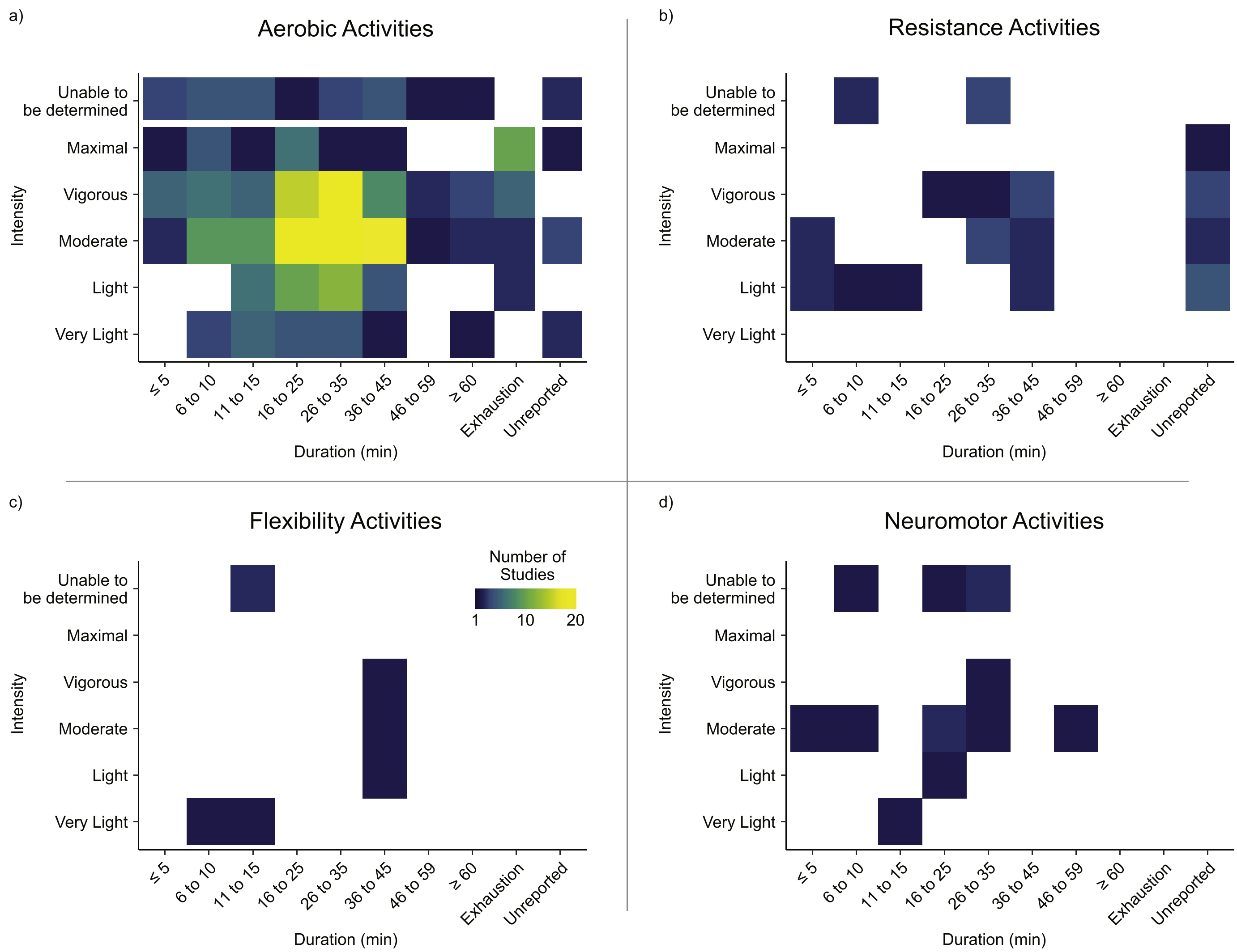


**Fig. 4.** Illustration depicting the number of investigations assessing cognition following each intensity and duration of the activity for aerobic (a), resistance (b), flexibility (c), and neuromotor (d) activity types.

underlying mechanisms. Interestingly, recent evidence from van Dongen, Kersten, Wagner, Morris, and Fernández (2016) suggested that acute physical activity-induced enhancements in long-term memory could persist for up to 48 h following the bout of activity. Furthermore, evidence in rodent models has suggested an even longer effect of physical activity with enhanced object recognition 21 days after a single 30 min bout of treadmill running performed following training on an object recognition task (da Silva de Vargas, Neves, das Roehrs, Izquierdo, & Mello-Carpes, 2017). The extent to which such prolonged enhancements occur for cognitive domains other than memory has not yet been adequately investigated however.

As the post-physical activity period becomes more protracted, it is of increasing importance to examine and report on what participants do between the cessation of the experimental conditions and the onset of the cognitive assessments. The nature of the activities engaged in during this period may moderate the impact of physical activity on cognition. That is, if participants continue to be physically active or engage in cognitively taxing activities following the experimental condition the effects of the experimental condition may be obfuscated. While such considerations are clearly critical if they differ between the physical activity and control conditions, with greater periods of time between the cessation of activity and the cognitive assessment there is greater opportunity for confounding factors to intervene. Therefore, reporting the activities of these intervening periods may facilitate a greater understanding of differences between studies. Of further consideration, the persistence of the cognitive after effects of a single bout of physical activity may also be dependent upon the characteristics of the dose of activity (i.e., intensity, duration, and type). For instance, enhancements in cognition may be immediately evident upon termination of light to moderate intensity bouts of physical activity whereas enhancements in cognition following higher-intensity physical activity may not be evident until after a 'cool-down' period. Indeed, consistent with such an assertion, in their meta-analytic review, Chang, Liu, et al. (2012), observed that lighter intensity activities had the largest effect immediately after physical activity whereas cognitive enhancements induced by higher intensity activities were greater after a delay of at least 1 min. Yet, given the paucity of research investigating more prolonged time periods following physical activity, we have limited understanding of the longevity of the cognitive after effects following acute bouts of physical activity, much less an understanding of how physical activity characteristics may moderate these effects.

### 1.3. *What dose of physical activity is sufficient to induce changes in cognition?*

While previous meta-analyses and reviews have heavily focused upon the relationship between the intensity of physical activity and resulting improvements in cognition (Chang, Labban, et al., 2012;

Etnier et al., 1997; Lambourne & Tomporowski, 2010; Ludyga et al., 2016; Tomporowski, 2003a, 2003b; Tomporowski & Ellis, 1986), it is important to consider how characterizing the dose of activity might affect changes in cognition following physical activity. Conceptually, characterizing just the intensity of an activity may well be insufficient as a unitary construct of the physical activity dose, as from an energetic perspective it is also necessary to consider the duration and type of activity. In order to provide insights into the particular dosages of physical activity assessed within the literature, we categorized each study based upon the intensity, duration, and type of activity. Classification of the intensity was performed using the cut points and criteria provided in Table 6.1 of ACSM's (2018) Guidelines for Exercise Testing and Prescription (10th ed.). The duration of the activity was quantified as the total time spent exercising, including any warm-up or cool-down periods. Finally, the type of physical activity was classified into the following categories: aerobic, resistance, flexibility, and neuromotor (American College of Sports Medicine, 2018). Aerobic activities were those consisting of endurance related activities such as walking, running, cycling, and aerobics. Studies utilizing free weights, machines with stacked weights or pneumatic resistance, and resistance bands were classified as using resistance activities. Studies utilizing activities comprising ballistic or bouncing stretches, dynamic or slow movement stretches, static stretching, and active static stretching were classified as using flexibility activities. Finally, activities involving motor skills, balance, coordination, gait, and agility/proprioceptive training as well as activities such as tai chi, qigong, and yoga were classified as neuromotor activities. To facilitate interpretation, the frequency of the dose of physical activity utilized is presented as a heat map in Fig. 4, showing the intersection of the activity intensity and duration for each type of activity.

### 1.3.1. Intensity

Within the literature, a prominent supposition is that enhancements in cognition should occur under moderate physical activity intensities, with diminished effects under lighter and more vigorous intensities consistent with an inverted-U perspective (Bender & McGlynn, 1976; Davey, 1973; Hillman, Kamijo, & Pontifex, 2012; Weingarten & Alexander, 1970). However, others have suggested that this intensity-dependent association may differ as a function of the type of task, such that lower-level cognitive tasks may benefit more from vigorous physical activity intensities (McMorris, 2016). Indeed, consistent with such an assertion, Chang and Etnier (2009b) observed the greatest enhancements in information processing following high intensities of resistance activity, whereas aspects of cognitive control were enhanced to a greater extent following moderate intensity resistance activity. Nevertheless, meta-analyses of the present literature have been equivocal to-date; with cognitive enhancements instead being observed for any intensities at or above light aerobic physical activity (Chang, Labban, et al., 2012; Lambourne & Tomporowski, 2010; McMorris, 2016). However, as evident in Fig. 4, within the aerobic physical activity literature the vast majority of research in this area has utilized moderate (58% of the literature) to vigorous (44% of the literature) intensities of physical activity, with 13% of studies failing to provide sufficient details from which to determine the intensity of the activity. Given the paucity of studies investigating other intensities, it may be premature to make strong statements about intensity-dependent findings. Further, it is important to acknowledge that there remains a lack of consensus regarding the best way to set the intensity of the physical activity and therefore a wide variation in how intensity is set and interpreted. Moreover, the method of setting intensity varies with the type of activity (i.e., aerobic, resistance, flexibility, and neuromotor) being investigated. Accordingly, a number of different ways of setting/characterizing intensity are provided below for consideration as investigators new to this area of research begin developing their own experiments. Given the current state of the literature, it would seem premature to specifically claim any one approach as superior – as each has particular advantages and weaknesses.

Many studies in the literature examining the after effects of aerobic physical activity have simply utilized percentages of measured or estimated maximal heart rate using a zero-to-peak approach (i.e., percent of maximum heart rate) to set intensity. While easy to compute and having potentially greater external utility in terms of what could be employed in school or work-based programs, this approach suffers from delimitations related to not accounting for the true range of cardiac capacity. Accordingly, the American College of Sports Medicine (2018), recommends that when basing physical activity prescriptions only on heart rate that the heart rate reserve (HRR) method be utilized to determine physical activity intensity. This approach determines the range of cardiac capacity from resting to maximal heart rate and sets the intensity based upon that range (i.e., [(maximum heart rate – resting heart rate) * %target intensity] + resting heart rate). Therefore, if an individual had a maximum heart rate of 195 beats per minute and a resting heart rate of 70 beats per minute, moderate intensity physical activity (between 64 and 76% of heart rate max) would fall between 125 and 148 beats per minute, based on the zero-to-peak approach. In contrast, the heart rate reserve approach would set a moderate intensity (between 40 and 59% of HRR) as a heart rate between 120 and 144 beats per minute. The difference between the intensities identified by these two approaches grows wider as resting heart rate increases and/or the range of cardiac capacities decreases. Thus, the heart rate reserve approach better enables setting physical activity intensity based on an individual's true range of cardiac capacity. The benefit of either of these methods is that they rely only upon measures of heart rate and can employ estimates of maximal heart rate if measures of the true maximal heart rate are not available — enhancing the practical application of these approaches. However, the gold-standard recommendation is to set intensity based upon a percentage of aerobic capacity reserve (%$VO_2R$; i.e., [($VO_2max$ – $VO_2rest$) * %target intensity] + $VO_2rest$) as it better accounts for individual differences in tolerance to aerobic physical activities (American College of Sports Medicine, 2018; Dalleck & Dalleck, 2008). The intensity of the activity could then be gauged by assessing oxygen consumption relative to the $VO_2R$, or by using the heart rate associated with the $VO_2R$ intensity. Unfortunately, to date, limited research has employed aerobic capacity reserve as a method of quantifying the intensity of acute physical activity investigations.

Yet, others have argued that the utilization of these methods of setting physical activity intensities as a function of light, moderate, vigorous, or near maximal to maximal are arbitrary and provide little insight into the contribution of aerobic and anaerobic metabolism (Hall, Ekkekakis, & Petruzzello, 2010; Heck et al., 1985; Kashihara & Nakahara, 2005; McMorris, 2016). Accordingly, the argument therein is that the after effects of physical activity on cognition may be dependent upon the degree to which the activity requires aerobic relative to anaerobic energy metabolism. Therefore, consistent with the shift in research investigating the after effects of physical activity on affective states, it has been suggested that intensities should be set relative to the percent of anaerobic threshold (Hall et al., 2010; McMorris, 2016). Such an approach would better ground discussion of physical activity intensity within a biological basis and could potentially facilitate a greater understanding of the biochemical factors contributing to changes in cognition following physical activity.

Conversely, rather than rely upon physiological parameters for establishing intensity; a closer association between intensity and the cognitive after effects of physical activity may occur when psychological parameters of intensity are utilized. That is, on any given day an individual may differentially perceive the level of effort required to engage in activity at an intensity fixed using physiological parameters such as heart rate. This subjective interpretation of the effort, stress, discomfort, and/or fatigue experienced during physical activity is collectively known as perceived exertion and can be assessed by having the individual rate their level of exertion on an ordinal scale (Robertson & Noble, 1997). The most well-known of these scales is the Borg RPE scale

(Borg, 1998) which ranges from 6 (no exertion) to 20 (maximal exertion) with the numeric rating generally approximating the heart rate observed at the given intensity (i.e., an RPE of 6 equates to a heart rate of approximately 60 beats per minute). However, the OMNI RPE scale (Robertson et al., 2000) has been shown to exhibit greater reliability and validity than the BORG RPE scale given that it integrates pictographs alongside descriptive anchors and a more intuitive scale ranging from 0 (not tired at all) to 10 (very, very tired; Pfeiffer, Pivarnik, Womack, Reeves, & Malina, 2002). While physiological measures of intensity generally correlate with perceived exertion, the argument for utilizing psychological measures is that they represent the complex integration of a wide assortment of physiological cues (e.g., heart rate, carbon dioxide production, glucose availability, hormone and temperature regulation) and psychosocial factors (e.g., perception of pain, emotional or mood states, and situational settings; Robertson & Noble, 1997). Thus, quantifying intensity utilizing perceived exertion may capitalize on the mind's ability to integrate these various cues and allow for a stronger association to be observed between intensity and changes in cognition following the cessation of physical activity.

Collectively, these various approaches each attempt to characterize intensity with regard to different physiological (e.g., cardiac capacity vs. energy metabolism) or psychological parameters (perceived exertion). The particular approach utilized by an investigation should then necessarily reflect the particular research question and the broader contextual/external relevance in which the research question exists. Those investigations focusing on feasibility or clinical relevance of acute bouts of physical activity may be better served by utilizing intensity measures that are more easily accessible to the population of interest such as heart rate reserve and/or perceived exertion approaches. However, those investigations focusing on theoretical development and underlying mechanisms may find approaches focusing on aerobic capacity reserve and/or energy metabolism to be better suited to their needs. It is clear though that future investigations should take greater care in accounting for potential individual differences in cardiac capacity, the contribution of energy metabolism, and the level of perceived exertion that may confound our understanding of the association between intensity and changes in cognition.

#### 1.3.2. Duration

Inherently tied to the intensity is the duration of the acute bout of physical activity. That is, aerobic intensity is inversely related to the duration, such that as the intensity of the bout increases the potential maximum duration decreases. Nevertheless, there may be some minimum duration necessary for the mechanisms underlying these acute bouts of physical activity induced changes in cognition to become activated or at least optimized to the degree necessary to observe changes in cognition. At present, the vast majority of the extant literature has utilized durations lasting from 16 to 35 min (88% of the literature). Whereas, substantially less research has been conducted with durations of 10 min or less (28% of the literature) and lasting 46 min or longer (15% of the literature). In their meta-analytic review, Chang and colleagues (Chang, Labban, et al., 2012), observed that changes in cognition after physical activity were only observed following bouts lasting at least 11 min, with no enhancements being observed for bouts lasting 10 min or less. However, it is important to point out that such a finding does not necessarily indicate that crossing from 10 min to 11 min represents some key threshold but may rather be reflective of characteristics of those studies included within the meta-analysis. It is also necessary to consider that there may be some maximum duration of prolonged continuous physical activity at which confounds related to dehydration, and/or nutritional status may come into play as these factors may independently influence the degree to which cognition would be impacted following physical activity (Lieberman et al., 2005). Indeed, Chang and colleagues (Chang et al., 2015), observed superior performance on a Stroop task following cycling at 65% of HRR for 20 min, relative to following similar intensities of activity for 10 min and 45 min as well as a seated reading control.

Further, the influence of the duration of activity may be dependent upon an individual's tolerance and familiarity with the physical activity stimulus. A 30 min bout of activity might be relatively easy to complete for an individual who regularly engages in an hour long bout of activity, but may be quite difficult for physically inactive/sedentary individuals. Thus, it may be important to consider an individual's baseline level of physical activity and fitness when examining the extent to which the duration of physical activity impacts upon the after effects of physical activity on cognition. These relationships may also depend on the degree to which the activity was in steady-state activity or variable intensity bursts (Kao, Westfall, Soneson, Gurd, & Hillman, 2017). Accordingly, it is necessary for future investigations to acknowledge these delimitations in their experimental designs and in our attempts to make consensus conclusions from the existing data. Although speculative, perhaps a greater understanding of the influence of the dose of activity on acute physical activity-induced changes in cognition would be provided through future investigations reporting the total caloric cost of the dose of physical activity, because this measure takes into account both the intensity and duration of the activity. Finally, given the limited research in this area, further research is necessary to more precisely determine if key transition periods exist for physical activity-induced enhancements in cognition to manifest or disappear and the extent to which such transitions occur in a linear, curvilinear, or exponential fashion.

#### 1.3.3. Type

A key question, as the literature continues to advance, is the extent to which the type of activity matters for inducing changes in cognition following a single bout of activity. Indeed, an observation made within a meta-analysis by Lambourne and Tomporowski (2010) was that cognitive enhancements following physical activity were larger for cycling modalities (effect size = 0.23) than for running-based modalities of activity (effect size = 0.12). It is important to note that these differences may manifest as a result of a wide range of factors (attentional/neural demands placed upon motor control patterns to engage in the activity, metabolic differences in the activities, aspects of cognition assessed in the investigations, etc.). However, this finding highlights that physical activity-induced changes in cognition may differentially manifest based upon the type of activity utilized. Although the predominant modality of activity utilized within this area of research has been repetitive aerobic-type activities such as walking, running, or cycling (representing 90% of studies in the literature), a growing number of investigations are examining other modalities of physical activity (e.g. resistance, flexibility, and neuromotor).

The non-continuous nature of non-aerobic activities, however, introduces several other potential considerations. In the case of resistance activities for instance, intensity can be set based upon a percent of the maximal strength exhibited by a particular muscle group, but a number of questions still remain: how many muscle groups/what muscle groups should be targeted, how much rest should be provided in between each muscle group/set, and should the activity be isometric or isotonic. Although resistance training is typically viewed as an anaerobic activity due to the increased contribution of glycolytic energy systems (American College of Sports Medicine, 2018), it can also be done in the context of circuit training wherein the activity could be more appropriately construed as an aerobic-type activity due to increased contribution of oxidative phosphorylation. These questions ultimately get at the key question of what it is about the physical activity stimulus that is responsible for inducing changes in cognition. In this sense, the modality of activity may be less important than the underlying characteristics of the physical activity bout (i.e., the aerobic nature of the activity, the intensity, duration, and/or the extent to which the activity is in steady-state).

Another characteristic speculated to be of particular importance is the extent to which the physical activity is socially or cognitively engaging (Best, 2010; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009). Some evidence for this assertion is drawn from an investigation by Pesce et al. (2009) who observed enhancements on a free-recall word memory task immediately after physical activity involving team-based games but not after circuit training; although, after a 12-min delay, free-recall word memory was enhanced following both types of physical activity. Similarly, Benzing, Heinks, Eggenberger, and Schmidt (2016) observed enhanced cognitive flexibility after exergaming, relative to a similar intensity of aerobic physical activity. While intriguing, some caution is warranted as the cognitive and attentional demands of more cognitively complex activities could mitigate the beneficial cognitive after effects of physical activity as neural resources are taxed to a greater extent in order to regulate the physical activity behaviors. For instance, in an investigation conducted by O'Leary et al. (2011), changes in attentional resource allocation (as indexed by the P3 event-related brain potential) following a bout of cognitively engaging exergaming were attenuated relative to aerobic physical activity on a treadmill at an equivalent cardiovascular intensity, but slightly elevated relative to seated rest (O'Leary et al., 2011). Further, Berman, Jonides, and Kaplan (2008) examined the effects of physical activity environments on working memory and indicated that task performance improved after walking in nature, but not after walking in urban areas. They suggested that, based on attention restoration theory (Kaplan, 1995), walking in nature — which they posit requires lesser attentional demands relative to walking in urban areas — can provide a chance to replenish cognitive abilities. Stated differently, the urban environments that necessitated greater attentional demands induced cognitive fatigue, which in turn resulted in inferior working memory performance. These findings are diametrically opposed to the above studies indicating that cognitively engaging physical activity was more beneficial for enhancing cognitive function. Thus, moving forward, future investigations should consider the potential ramifications of the context in which the physical activity takes place, the cognitive load imposed by the activity, and the characteristics of the physical activity beyond the more basic classifications of an activity by modality.

### 1.4. What are some other potential moderating factors?

As the investigation into the after effects of acute bouts of physical activity on cognition is still in its relative infancy, we have limited information elucidating what factors are truly important in this relationship. Nonetheless, for the purpose of better orienting investigators in this area, we have highlighted below a few variables of interest which should be practically relevant or relevant from the perspective of understanding the dose of the physical activity stimulus. Of the moderators discussed in the present review, the relationship of age (Caterino & Polack, 1999; Chu et al., 2017; Dimitrova et al., 2016; Ellemberg & St-Louis-Deschênes, 2010; Kamijo et al., 2007) and aerobic fitness (Bullock & Giesbrecht, 2014; Chu, Chen, Hung, Wang, & Chang, 2015; Heckler & Croce, 1992; Hogan et al., 2013; Sjöberg, 1980; Stroth et al., 2009; Themanson & Hillman, 2006; Tsai et al., 2014) with acute physical activity-induced changes in cognition have been examined more extensively than baseline performance (Drollette et al., 2014).

#### 1.4.1. Baseline Performance

From a practical perspective, individuals with the poorest performance at pretest have the greatest opportunity for improvement, whereas this opportunity is limited for individuals performing at a very high level (Drollette et al., 2014). Should we then conclude that the high performing group truly does not benefit from physical activity or that the underlying cognitive construct of interest is stable/at its peak ability? From this perspective, it is necessary to acknowledge that the constraints imposed by the method of assessment may artificially induce such limiting factors either through ceiling or floor effects. Stated more plainly, it is difficult to gain an understanding of differences in cognition if the outcome variable does not have room to improve. If participants in a study performed at 100% accuracy or were responding at the limits of motor speed, would it be appropriate to suggest that physical activity had no benefit? Accordingly, a key consideration for future investigations in this area is in selecting cognitive tasks or altering base parameters to ensure a developmentally appropriate challenge with sufficient range so as to avoid these confounds. It may well be that a particular group that exhibits atypical levels of baseline performance (i.e., poorer/superior performance on a task relative to typical individuals) may be more/less sensitive (i.e., exhibit larger/smaller effects) to single bouts of physical activity. Indeed, such findings may be of a great deal of interest towards understanding the clinical importance of acute physical activity or the underlying mechanisms if the atypical level of performance is the result of underlying physiological differences. However, without taking care to ensure that performance is not being artificially constrained, the interpretation of the effects of acute bouts of physical activity on cognition in such populations are of limited utility.

#### 1.4.2. Age

At present we still have limited understanding of the extent to which the after effects of acute physical activity may differentially influence cognition across the lifespan. In order to provide insight into the populations assessed within the acute physical activity and cognition literature, we characterized the population of each study into the following chronological age categories: Infant (less than 1 year old), Early Childhood (1–4 years old), School-Aged (5–12 years old), Adolescence (13–17 years old), Young Adult (18–34 years old), Middle-Aged Adult (35–59 years old), Late Middle-Aged Adult (60–74 years old), and Older Adult (more than 74 years old; Malina, Bouchard, & Bar-Or, 2004). As illustrated in Fig. 5, 63% of the present literature has focused on young adult populations, with relatively few investigations assessing other populations across the lifespan.

In their meta-analysis of the literature, Chang, Liu, et al. (2012), observed the greatest post physical activity enhancements in cognition in high-school aged children and adults over the age of 31, with college-aged young adults exhibiting smaller effects. Similarly, a meta-analysis by Ludyga and colleagues (Ludyga et al., 2016), observed the greatest post-physical activity enhancements in older adults (50 years of age and above) and preadolescent children (6–12 years of age), when focusing only on investigations assessing aspects of cognitive control. Although these findings provide early evidence that the effects of physical activity may differ across the lifespan, given the relative paucity of research investigating non-young adult populations, such findings should be interpreted cautiously.

Further, a critical question is what mechanism would be specific for

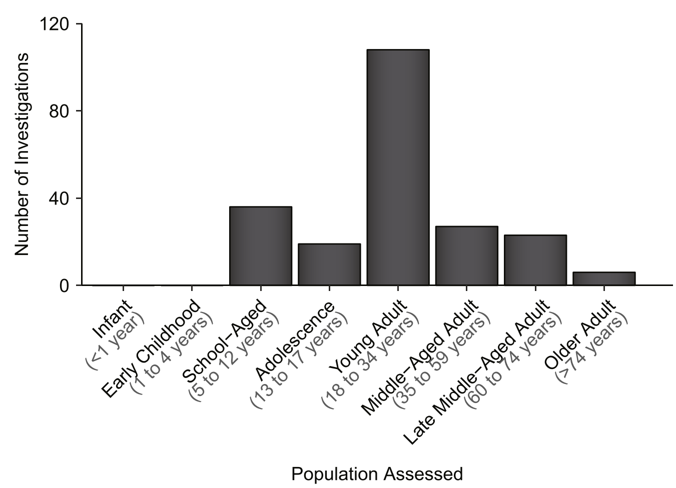


**Fig. 5.** Illustration of the number of investigations conducted within each population.

acute bouts of physical activity to induce cognitive enhancements in school-aged children and older adults, but not in college-aged young adults? Pragmatically, however, it is also necessary to acknowledge that such findings may simply occur as a function of the cognitive assessments employed in investigations in these populations. That is, much like the argument for consideration of the baseline level of performance, the after effects of acute bouts of physical activity on cognition may also be diminished in populations such as college-aged young adults as their cognitive operations may be at such a high level that there may be little room for improvement. In other words, the lack of an effect for college-aged young adults may simply be the result of a ceiling effect in the cognitive assessments employed as performance is often greater than 90% accurate (Bullock & Giesbrecht, 2014; Kamijo et al., 2007; O'Leary et al., 2011; Themanson & Hillman, 2006; Yagi, Coburn, Estes, & Arruda, 1999).

#### 1.4.3. Aerobic Fitness

The acute physical activity and cognition relationship may also be moderated by aerobic fitness. The attribute of aerobic fitness appears positively associated with many aspects of cognition, including similar aspects of cognitive control that are influenced by acute bouts of physical activity (Etnier et al., 1997; Hillman, Erickson, & Kramer, 2008). Thus, from this perspective, it may be that individuals with greater levels of aerobic fitness may be more likely to run into ceiling effects on cognitive assessments, while individuals with lower levels of aerobic fitness may have greater opportunity for improvement following a bout of physical activity. Given its relationship to learning and memory (Hillman et al., 2008), superior aerobic fitness might also predispose an individual towards more rapid acquisition of a task and accumulation of practice effects. Second, an individual's level of aerobic fitness may moderate the physiological demands and/or perception of the activity incurred by the physical activity stimulus (American College of Sports Medicine, 2018). That is, aerobic fitness may have a greater or lesser impact dependent upon the intensity, duration, and type of activity investigated. As the construct of aerobic fitness describes an individual's tolerance for sustaining aerobic physical activities, aerobic fitness may have little moderating influence for non-aerobic types of activity or for shorter duration bouts of aerobic activity. However, it would seem logical that aerobic fitness would be particularly relevant for sustaining longer duration bouts of aerobic activity and therefore might play a moderating role in the after effects of long-duration physical activity on cognition. In their meta-analytic review, Chang and colleagues (Chang, Labban, et al., 2012) observed that fitness was only a moderating variable when cognition was assessed immediately after the cessation of a bout of physical activity but not when cognition was assessed after a delay, suggesting that the influence of aerobic fitness may be restricted to only the recovery period. Lastly, it may be that aerobic fitness plays a moderating role by priming the underlying neurobiological mechanisms which ultimately give rise to acute physical activity-induced changes in cognition (Chang, Labban, et al., 2012). Clearly, more rigorous investigations into aerobic fitness as a moderating influence are necessary to better elucidate the nature of and degree to which aerobic fitness moderates the cognitive after effects of acute bouts of physical activity.

### 1.5. What are the mechanisms driving these effects?

While the evidence for the beneficial after effects of acute bouts — or doses — of physical activity for cognition continues to grow, the neurobiological mechanisms by which this process occurs are still unknown. Although research has investigated how neurobiological factors change in response to acute bouts of physical activity both within human and animal models — providing key insights into the physiological impacts of physical activity engagement; a critical impediment to classifying these neurobiological factors as 'mechanisms' is in relating such physiological changes to changes in cognitive processes. Thus, without empirical evidence demonstrating that these neurobiological factors mediate or at the very least exhibit some association with changes in cognition induced by acute bouts of physical activity, it is inappropriate to conclude that such neurobiological factors serve as mechanisms. Ultimately, an understanding of these mechanisms is important for informing what aspects of cognition may be influenced or immune to the effects of physical activity and what activity characteristics may maximize these enhancements. Further, a greater understanding of the neurobiological mechanisms may enhance our understanding of how single doses of physical activity eventually amass to create more long-lasting changes in cognition associated with habitual physical activity engagement and physical health attributes. Accordingly, below we discuss several popular hypothesized mechanisms and posit others that may warrant further research.

#### 1.5.1. Arousal

Arguably, the most popular mechanism attributed to enhancements in cognition observed following a bout of physical activity is arousal. The term arousal refers to a multidimensional construct that has physiological (somatic), cognitive (thoughts/motivations), and affective (emotions) components (Eysenck, 1982). Given the nature of this construct, the term arousal is somewhat problematic as it tends to be utilized as a catch-all term to describe that something is activated or requires energetic resources (Duffy, 1957). Nevertheless, a sizable body of literature has observed a relationship between arousal and performance. A prominent demonstration of this association is provided by Yerkes-Dodson (Yerkes & Dodson, 1908) who utilized electric shock to induce various levels of arousal in mice and observed that the mice more rapidly learned a simple discrimination task when arousal level was high, relative to when arousal levels were low. However, in response to a more difficult discrimination task, learning was optimal under moderate levels of arousal with poorer performance observed under lower and higher levels (Yerkes & Dodson, 1908). In this sense, physical activity is thought to be just another form of stressor — in the same vein as electric shock — that can be used to induce various states of arousal (McMorris, 2016). Indeed, similar to changes in arousal induced by cognitive and emotional stressors, physical activity is associated with activation of the sympathetic nervous system as assessed through heart rate and skin conductance (Poh, Swenson, & Picard, 2010). While there is little disagreement that physical activity may be a stressor, it is important to note that this characterization may not uniformly apply to all durations, types, and modalities/characteristics of activity. Further, depending upon the duration, type, and modality of the activity, the cognitive evaluations of the physical activity as a stressor may be drastically different across individuals. Indeed, some may even perceive certain types of physical activity to be anxiolytic (Petruzzello, Landers, Hatfield, Kubitz, & Salazar, 1991).

A popular assertion is that cognition should be enhanced at moderate levels of arousal with diminishing enhancements occurring under lesser or greater levels of arousal, consistent with an inverted-U or J (Davey, 1973; Hogervorst et al., 1996; Weingarten & Alexander, 1970); conversely, others posit that this relationship may differ depending upon the aspect of cognition assessed (McMorris, 2016). As a mechanistic statement, indicating that cognition is enhanced because the brain/body is under moderate levels of arousal (i.e., activation) is not a particularly satisfying explanation. While it is important to acknowledge that psychological constructs may not have a clear biological basis (Miller & Keller, 2000), common measures of arousal such as heart rate and skin conductance have been observed to return to baseline rapidly after the cessation of physical activity (McMorris, 2016). From the perspective of assessing the after effects of physical activity on cognition, what is the underlying mechanism/relationship if arousal has returned to baseline but enhancements in cognition are still observed? Accordingly, to advance our understanding of the after effects of physical activity on cognition, it is necessary to move beyond generic catch-all mechanistic attributions and begin testing the distinct factors commonly clustered within the term arousal.

#### 1.5.2. Activation of the Locus Coeruleus Norepinephrine system

One key component of the arousal system is the locus coeruleus norepinephrine system (Benarroch, 2009). The locus coeruleus, part of the reticular activating system, is a collection of noradrenergic neurons located within the brainstem that is involved in modulating the neural system's level of alertness (Kinomura, Larsson, Gulyás, & Roland, 1996). In particular, concurrent evidence across both human and nonhuman animal models suggests that activation of the locus coeruleus and the associated release of norepinephrine serve an important role in influencing the attentional state of the brain (Sara & Bouret, 2012). Modern perspectives of the locus coeruleus suggest that this system has a dual pattern of activation. During tasks requiring focused attention, neurons in the locus coeruleus exhibit a moderate level of tonic (baseline) activation that enables phasic (dynamic) bursts of activity to occur coupled with the execution of a response to task-relevant stimuli (Aston-Jones & Cohen, 2005). Importantly, the activation pattern of the locus coeruleus exhibits a causal relationship with behavioral performance and attention, as microinjection experiments have demonstrated that increasing the tonic activation of this system increased distractibility and decreased performance, whereas suppressing tonic activation to moderate levels served to decrease distractibility and increase performance in primate models (Aston-Jones & Cohen, 2005). Such moderate levels of tonic (baseline) activity in the locus coeruleus may therefore entrain other neural systems to limit responsiveness to irrelevant stimuli, thereby preventing spurious distractions (Bouret & Sara, 2005), with the task-related phasic (dynamic) bursting of activity serving to selectively facilitate goal-directed behaviors by providing a brief attentional filter (Aston-Jones & Cohen, 2005). This short-term attentional filter may therefore allow for more rapid online adjustments in behavioral responses and strategic approaches to maximize performance (Bouret & Sara, 2005). Conversely, the attentional system exhibits a greater level of distractibility when the locus coeruleus has greater tonic (baseline) activation (Bouret & Sara, 2005).

In this context, cognitive enhancements induced by acute bouts of physical activity may — in part — result from physical activity regulating the locus coeruleus to maintain moderate levels of tonic (baseline) activation, thereby entraining other neural systems to focus attention and enabling task-related phasic bursts of locus coeruleus activity to facilitate attentional control mechanisms. Treadmill-based acute aerobic activity has been shown to protect against depletion of norepinephrine within the locus coeruleus, amygdala, and hippocampus in nonhuman animal models (da Silva de Vargas et al., 2017; Dishman, Renner, White-Welkley, Burke, & Bunnell, 2000) in a manner that would be consistent with more moderate levels of tonic (baseline) activity (Aston-Jones & Cohen, 2005), however, there is no evidence that acute bouts of physical activity directly affects locus coeruleus function. Clearly, further research is necessary to determine the extent to which single bouts of physical activity change neural activity in the locus coeruleus norepinephrine system and to what extent such changes may underlie the differences in cognition observed following physical activity.

#### 1.5.3. Cerebral Blood Flow

Another popular mechanism attributed to underlie the after effects of physical activity on cognition is increased cerebral blood flow, which manifests given the increased cardiac output during activity (Ogoh & Ainslie, 2009). Such beliefs are likely drawn from cross-sectional studies where greater cardiovascular fitness has been associated with increased cerebral blood flow (Ainslie et al., 2008), with the idea that the greater cerebral perfusion may facilitate cognitive processing as a result of increased metabolic resource availability and waste clearing (Delp et al., 2001; Pereira et al., 2007; Vingerhoets & Stroobant, 1999). Interestingly, consistent with the inverted-U or J hypothesis regarding the relationship between physical activity intensity and enhancements in cognition following a bout of physical activity, a meta-analytic review observed increased cerebral blood volume and cerebral oxygenation during moderate to vigorous intensities but not during light or very intense activities (Rooks, Thom, McCully, & Dishman, 2010). However, recent findings by Pontifex and colleagues (submitted), observed that changes in cerebral blood flow were not sustained following the termination of the physical activity stimulus, during the period in which cognitive enhancements have been previously observed. Although the general attribution has been towards cerebral blood flow as a potential mechanism, it is also necessary to acknowledge that cognitive enhancements following physical activity may relate to a cascade of cerebral vascular responses which may have greater or lesser relevance for inducing changes in cognition following physical activity (Ogoh & Ainslie, 2009). Clearly then, further research is necessary to examine the extent to which reactivity of cerebral blood flow during physical activity relate to cognitive improvements following physical activity, in addition to examining similar relationships with other cerebral vascular responses.

#### 1.5.4. Catecholamines

Another proposed mechanism for physical activity-induced changes in cognition is increases in catecholamines (Cooper, 1973); see (McMorris, Turner, Hale, & Sproule, 2016). Although most commonly hypothesized for modifying cognition *during* physical activity rather than *after* physical activity, the crux of this mechanistic hypothesis is that catecholamines are by nature neuromodulatory. Thus, if physical activity serves to increase production, availability, absorption, or regulation of catecholamines, then the nervous system would respond and would continue to be responsive for some period of time following the cessation of the physical activity stimulus. Some support for this hypothesis is provided by da Silva de Vargas and colleagues (da Silva de Vargas et al., 2017) who blocked physical activity-induced object recognition learning in rodent models by pharmaceutically inhibiting beta-adrenergic receptors. When norepinephrine binds to beta-adrenergic receptors, a cascade of pathways are activated which serve to increase neuronal excitability and are involved in long-term memory formation and synaptic plasticity (O'Dell, Connor, Guglietta, & Nguyen, 2015). Given the findings that inhibition of these receptors blocked physical activity-induced changes in cognition, the catecholamine norepinephrine may be responsible for inducing such changes in cognition following acute bouts of physical activity. Further, in a separate group of rodents, hippocampal infusions of norephinephrine facilitated object recognition learning at a level comparable to the cognitive enhancements observed 21 days following a single 30 min bout of treadmill running (da Silva de Vargas et al., 2017). Thus, these data serve to implicate norephinephrine as a potential mechanism underlying physical activity-induced enhancements in cognition. Together, these findings provide evidence in support of the assertion that catecholamines may contribute to physical activity-induced changes in cognition. A critical area for future research is in continuing to examine the extent to which physical activity-induced changes in catecholamines moderate the after-effects of bouts of physical activity on cognition so as to determine if such findings are specific for aspects of memory or generalize across domains of cognition.

#### 1.5.5. Neurotrophic factors

Finally, no review of potential mechanisms underlying physical activity-induced enhancements in cognition is complete without discussion of neurotrophic factors such as BDNF (brain-derived neurotrophic factor), IGF-1 (insulin-like growth factor 1), and VEGF (vascular endothelial growth factor). Within research investigating the influence of chronic physical activity on cognition, the focus on these biomolecules has been in regards to their role in supporting the development, survival, and differentiation of neurons (Gómez-Pinilla & Feng, 2012). However, these neurotrophic factors also play a neuromodulatory role in promoting and maintaining synaptic connectivity (Huang &

Reichardt, 2001), which suggest that they may also underlie cognitive enhancements after a single bout of physical activity. Accordingly, these neurotrophic factors are known to directly influence cortical processing and intensity-dependent increases in concentrations of BDNF (Knaepen, Goekint, Heyman, & Meeusen, 2010), IGF-1 (Kido et al., 2016; Schwarz, Brasel, Hintz, Mohan, & Cooper, 1996), and VEGF (Jensen, Pilegaard, Neufer, & Hellsten, 2004; Kraus, Stallings, Yeager, & Gavin, 2004) have been found following a single bout of physical activity. Because of these findings, these neurotrophic factors have been hypothesized to underlie changes in cognition following physical activity (McMorris et al., 2016; Piepmeier & Etnier, 2015). While research specifically investigating these factors as neurobiological mechanisms for acute physical activity induced enhancements in cognition has been limited, evidence at least with regard to BDNF has so far been equivocal. Specifically, Winter and colleagues (Winter et al., 2007) observed an association between learning performance and greater maintenance of BDNF concentrations following high-intensity activity. However neither Ferris, Williams, and Shen (2007) nor Tsai et al. (2014) observed any association between physical activity-induced changes in BDNF concentration and performance on an inhibitory control task (Ferris et al., 2007) or a visuospatial attention task (Tsai et al., 2014). Further research is warranted to investigate the extent to which these neurotrophic factors may underlie the cognitive after effects of single bouts of physical activity. Accordingly, a greater understanding of the acute influence of these neurotrophic factors would be of particular interest for informing how single bouts of physical activity eventually amass to create more sustained alterations in cognition associated with chronic physical activity behaviors.

## 2. Methodological considerations

In addition to providing some discussion regarding prominent themes present in the literature, it is also important to consider some of the implications imposed by particular methodological approaches for gaining insight into the effect of acute bouts of physical activity on inducing cognitive enhancements. Indeed, as this body of literature integrates the domains of kinesiology, cognitive psychology, and neuroscience; it is necessary to integrate best-practice approaches from each area — as drawing methodological approaches from singular domains without appropriate constraints may limit the interpretability of the findings. The sections below, thus provide a selection of methodological considerations regarding the implications imposed by the selection of various experimental designs, control conditions, and cognitive assessments. Finally, recommendations regarding statistical and reporting considerations are provided to better facilitate transparency within future investigations in this area of research.

### *2.1. What are suitable research designs?*

Although research in this area has utilized a wide assortment of designs, the key attributes common to these research designs enable them to be clustered into five main approaches (see Fig. 6). These approaches are generally differentiated by their between- or within-subjects nature as well as the extent to which cognition is assessed prior to and following the physical activity and control periods. To provide some perspective regarding the popularity of these various research designs, the present review categorized the extant literature using these design classifications. As evident in Fig. 7, no singular research design has emerged as particularly prominent within the literature. This is perhaps not surprising given their respective limitations. However, moving forward, research investigations in this area should make a more conscious effort to select the most rigorous design appropriate for their measures. Further, the subsequent publication of any findings should make clear the experimental design whose characteristics lead the investigators to select a particular research approach. Doing so would not only enhance readers' conceptual understanding but would

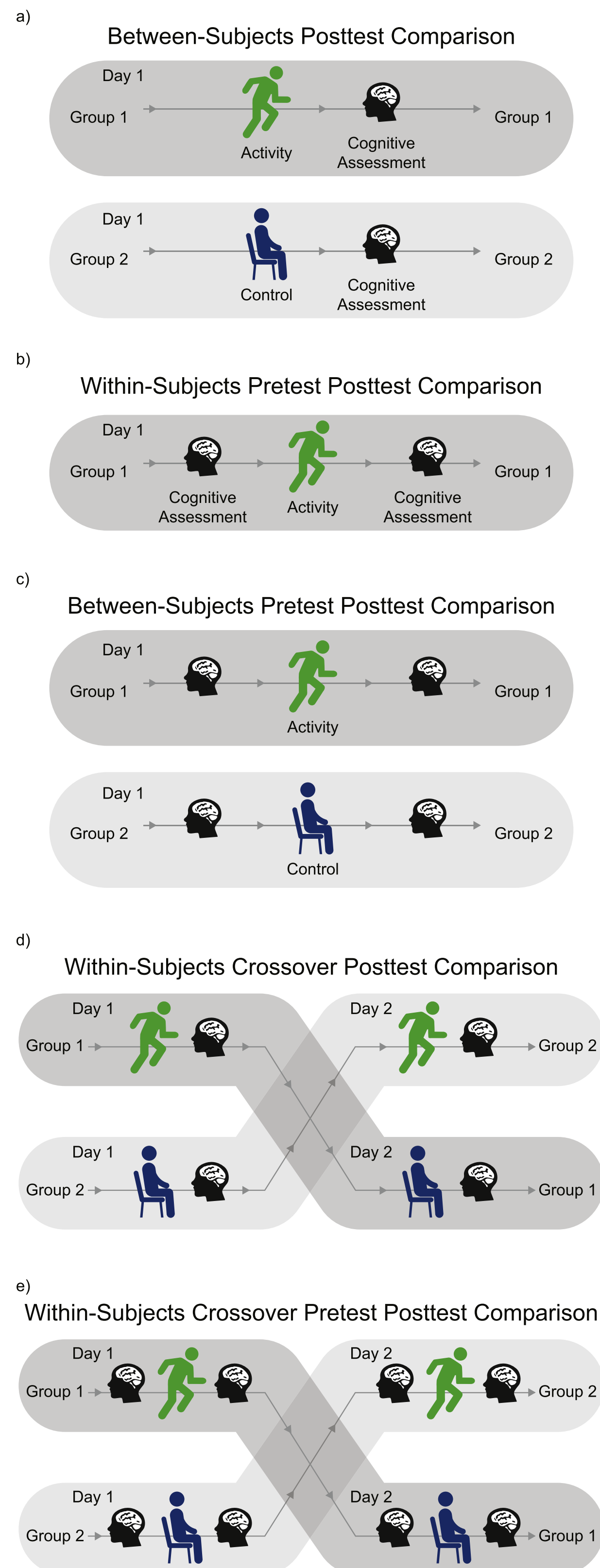


**Fig. 6.** Illustration representing how each research design incorporates the cognitive assessments relative to the physical activity and control conditions.

also contribute towards research in this area by continuing to enhance experimental rigor.

Although no singular approach has emerged as the standard — as each has its own particular strengths and weaknesses; two research

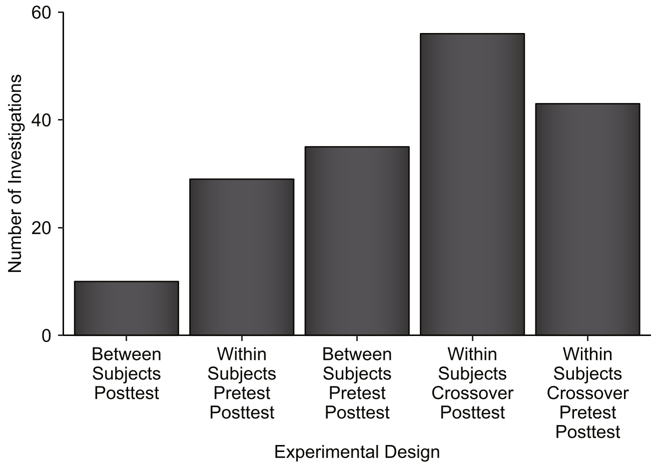


**Fig. 7.** Illustration of the number of investigations utilizing each research design.

designs have been identified as potentially problematic. That is, in investigations utilizing between-subjects posttest only comparisons (Fig. 6a), cognition is only assessed at a singular time for each participant following the experimental condition, with some participants engaging in physical activity and others engaging in a control condition. The critical limitation of such a design is that it does not allow for determining the *effect* of acute bouts of physical activity. Rather, the nature of the design necessarily limits discussion to *differences* between one group and another and inferring that such differences must be due to physical activity. With only a single testing point, such conclusions are tenuous given that the construct of cognition is not stable over time. However, with sufficiently large sample sizes, random group assignment and the integration of proper covariates it would be logical to assume that differences between groups are attributable to physical activity engagement.

Investigations incorporating pre- and posttest assessments only following a singular physical activity intervention (without the semblance of a control group) — as in the within-subjects pretest posttest comparison design — are also potentially problematic (Fig. 6b). Such designs enable characterization of the change in performance directly resulting from the experimental manipulation. However, it is important to note that in this context, the presence or lack of an effect due to acute bouts of physical activity cannot be dissociated from that of learning, practice, or exposure to the cognitive assessment. That is, if an individual was asked to repeatedly complete a cognitive assessment, performance would be expected to improve as a result of learning and practice even without an intervention between exposures (Baenninger & Newcombe, 1989). Thus, improvements in cognition attributed to physical activity from designs where cognition is assessed only prior to and following physical activity or designs where cognition following physical activity is compared to some prior baseline period, could simply reflect changes induced by repeated exposure to the task rather than by being attributable to the experimental condition.

Accordingly, the strength of designs utilizing between-subjects pretest posttest comparisons (Fig. 6c) is in their ability to characterize how cognition changes in response to physical activity relative to how it changes in response to some control condition. The control condition thus provides for some index of differences in cognition that may occur as a result of repeated exposure to the cognitive assessment. However, in such designs it is particularly important to utilize an appropriate control for physical activity so as to be able to attribute the effects to the physical activity intervention rather than to other factors (Simons et al., 2016). Indeed, it is necessary to acknowledge the limitation imposed by having two different groups do two different interventions. If not appropriately controlled for in the random assignment of participants to either physical activity or control groups, individual differences or other personality attributes might enable one group to more rapidly acquire the task and accumulate practice effects or similarly alter performance characteristics. Investigations that use this design should take great care in controlling for potential individual difference factors between groups both in the formation/selection/randomization of the groups and the statistical analysis of the findings.

The within-subjects crossover posttest comparison design (Fig. 6d) characterizes differences in cognition following physical activity and control conditions within the same subject. In this design, all subjects engage in both the physical activity and control experimental conditions (on separate days), with the order of the experimental conditions counterbalanced across participants (i.e., the crossover). The strength of this approach being that each participant effectively serves as their own control, reducing the potential for individual difference-related confounds. However, two weaknesses of this experimental design are prominent. First, we still have limited understanding of the persistence of these post-physical activity induced changes in cognition. Thus, as this design requires that some participants complete the physical activity assessment and then return for the control assessment, scheduling the sessions too closely together may bias the approach against finding an effect as cognition may still be altered from the physical activity session (i.e., a carryover effect). The other critical limitation of this approach is that it fails to account for day-to-day variations in performance and any potential changes induced by the initial experimental condition. That is, the baseline level of performance on a task may vary depending upon a host of factors including the time of day (Blatter & Cajochen, 2007; Schmidt, Collette, Cajochen, & Peigneux, 2007), amount of sleep the night before (Alhola & Polo-Kantola, 2007; Williamson & Feyer, 2000), food or caffeine intake (Jarvis, 1993; Smith, Kendrick, Maben, & Salmon, 1994), and menstrual cycle (Hampson, 1990; Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Güntürkün, 2000; Wright & Badia, 1999). Although these factors would only hypothetically be relevant if participants engaged in different activities on each day, without an understanding of the level of cognitive performance on a task prior to an intervention, it is difficult to interpret the extent to which the intervention induces changes, when only posttest assessments are conducted. For example, an investigation by Pontifex, Parks, Henning, and Kamijo (2015) replicated previous observations that neuroelectric indices of attention (i.e., the P3 event-related brain potential) were elevated after a bout of physical activity relative to after a seated-rest control condition. However, when examined relative to pretest assessments, the findings were not that physical activity enhanced attention in response to a simple stimulus discrimination task but rather that prolonged seated rest resulted in decrements (Pontifex et al., 2015). Much of the neuroimaging work investigating the effects of acute bouts of physical activity on neuroelectric indices of cognition has relied on these post experimental condition comparisons out of concern for the complexity of data collection, analysis of large data sets, and lack of psychometric data for repeated assessment of these neuroimaging/psychophysiological measures. However, it could be argued that the methodological strength of these investigations could still be enhanced through the incorporation of pretest assessments for behavioral measures.

Ultimately, the most rigorous approach incorporates the key attributes of each of these designs, utilizing a within-subjects crossover design with both pretest and posttest assessments (Fig. 6e). In this design, all participants engage in both the physical activity and control experimental conditions (on separate days), with the order of the experimental conditions being counterbalanced across participants and cognition assessed prior to and following each experimental condition to isolate changes in cognition to those specifically induced by the experimental conditions. This design thus builds upon the strength of between-subjects pretest posttest comparisons and utilizes a within-subjects crossover approach to control for individual differences and the effect of learning/practice. That is, an inherent limitation of assessing cognition is that performance improves with repeated exposure as a result of learning/practice, however the potential for improvements in performance diminishes across repeated exposures to the task (Bartels, Wegrzyn, Wiedl, Ackermann, & Ehrenreich, 2010; Calamia, Markon, & Tranel, 2012; Collie, Maruff, Darby, & McStephen, 2003). Accordingly, the crossover approach utilizes the experimental design to control for the effect of learning/practice. The greatest improvements in cognition are likely to be observed for the group that engages in physical activity on the first day when the effects of physical activity and learning/practice may be the most pronounced. Consequently, this group should also exhibit the smallest effects on cognition for the second day of testing when the group engages in the control condition given the tapered learning/practice effect. Alternatively, the group that engages in physical activity on the second day should exhibit muted changes in cognition given the diminished potential for improvement to be observed, whereas the effects of the control condition performed on the first day should be more pronounced due to learning/practice. Thus, by collapsing across groups, the effects of learning/practice should be mitigated within both the physical activity and the control conditions. While the trend in the literature has been to examine potential Order (physical activity on day 1, control on day 2; control on day 1, physical activity on day 2) × Mode (physical activity, control) × Time (pretest, posttest) interactions, such statistical approaches effectively disregard the inherent strength of the experimental design in controlling for the effect of learning/practice and thus should be avoided particularly if the investigation is not adequately powered for the additional level of analysis. A critical limitation of this design, however, is that each participant must effectively perform the cognitive assessment at least four separate times, potentially inducing greater subject burden — particularly for those investigations employing multiple cognitive assessments. Further, the greater exposure to the cognitive assessment presents as a potential bias against observing enhancements in cognition given the increased likelihood that the participant's performance may approach some practice or developmental related ceiling, whereby enhancements in cognition are no longer observable. Additionally, although this design is particularly rigorous, it is also time-consuming and the nature of the cognitive assessments may preclude investigators from using it, as a result of the number of times the cognitive assessment must be repeated. Thus, it is important to acknowledge that although investigators should make the extra effort to utilize the strongest design possible, particular circumstances may necessitate utilizing less rigorous designs to minimize other potential confounds.

### 2.2. What is a suitable control for physical activity?

Despite the growing number of investigations in this area, there still remains a question regarding what an appropriate control for physical activity should be. That is, unlike drug research which can use a placebo to render participants blind to the experimental condition, participants in investigations of the effects of physical activity are aware of the physiological demands to which they are being exposed. Accordingly, in such instances it is important to consider the extent to which expectancy (also referred to as the Hawthorne effect) and motivation might contribute to the observed findings (Boot, Simons, Stothart, & Stutts, 2013; Green, Strobach, & Schubert, 2014). Similarly, it is also important to acknowledge the potential for bias to be introduced as a result of demand characteristics. If participants form an opinion regarding the hypothesized outcome of the experiment, they may subconsciously alter their behaviors to fit the hypothesis (Weber & Cook, 1972). At present, however, little research has been conducted quantifying the extent to which participants expect various physical activity and control conditions might induce changes in cognition, nor examining the relationship between physical activity-induced changes in cognition and the magnitude of the expectancy.

To provide some insight into the prevalence of different control approaches within the acute physical activity literature, the present review categorized the extant literature into using either a baseline control, a disengagement control, a cognitive engagement control, or an active control condition. The baseline control represents when baseline performance was assessed either on a separate day from the physical activity condition or on the same day preceding the experimental intervention(s), but this assessment was not used as a pretest during analyses. The disengagement control condition comprises passive sedentary activities during which no cognitive engagement occurs such as seated rest (on a chair or on a cycle ergometer) without talking to experimenters. The cognitive engagement control was comprised of cognitively engaging activities such as talking with others, watching a video, reading, playing a videogame, or participating in a classroom lesson. Finally, the active control conditions were those comprised of physical activities such as walking on the treadmill at the lowest speed with no grade, low intensity active stretching, or pedaling the cycle ergometer with no resistance.

Of these control conditions, the most prevalent approach has been to utilize either disengagement control or cognitive engagement control conditions (representing 75% of the extant literature), with approximately 19% of studies utilizing a baseline control and 13% of studies utilizing an active control condition (see Fig. 8). While no singular control condition has emerged as the standard within the literature, as each control has particular utility; the use of baseline control conditions should be avoided within future research. The justification for such an assertion is based upon well-established findings demonstrating that performance on a task is rarely stable. Performance on a task is sensitive to factors such as time of day, sleep, food/caffeine and menstrual cycle and performance should improve across repeated exposure to a task as a result of learning/practice. Thus, utilizing a baseline control as a comparison to the physical activity condition represents a fundamental design flaw undermining the extent to which effects can be attributed to acute bouts of physical activity.

Collectively, the choice of control condition should necessarily reflect and isolate the aspect of physical activity that is viewed as being critical for inducing improvements in cognition (Green et al., 2014). The use of disengagement control as the control condition has the benefit of being the conceptual antithesis of physical activity. However, from a mechanistic standpoint there are a number of broad differences that exist between physical activity and disengagement control including factors such as locomotion and motor control patterns, activation of the sympathetic nervous system, boredom, attentional engagement, and even body position may differ between conditions for investigations that utilize a sitting control relative to upright physical activity. Further, these conditions also tend to differ in the extent to

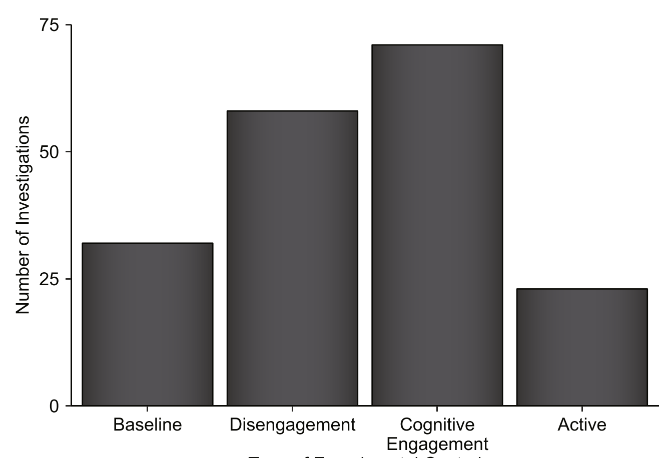


**Fig. 8.** Illustration of the number of investigations utilizing each experimental control.

which participants are socially engaged. Although speculative, differences in cognition may be induced as a result of variations in social interaction between conditions related to the presence of experimenters involved with monitoring the participants during physical activity relative to non-activity conditions (Levine, Resnick, & Tory, 1993). The use of cognitively engaging and/or active control conditions better satisfy perspectives that in order to appropriately gauge the effectiveness and clinical relevance of an intervention it is essential to utilize contact-control conditions that represent the current 'standard of care' or closely match the intervention to isolate the hypothesized mechanism of interest (Green et al., 2014; Simons et al., 2016). For instance, an investigation which observed enhancements in cognition resulting from acute bouts of physical activity in school-aged children would likely have greater clinical relevance when compared against behavioral management approaches currently used within the classroom as opposed to comparing the intervention against students sitting quietly with their heads on the table doing nothing. Similarly, the selection of a particular control condition should take care to isolate the characteristics of physical activity viewed as critical for enhancing cognition and minimize the extent to which the conditions differ in other ways. For instance, an investigation might elect to have participants watch an emotionally neutral video during both the physical activity and the control condition so as to minimize the attentional and affective differences between conditions (Ellemberg & St-Louis-Deschênes, 2010). Collectively, from a conceptual framework perspective, rather than altering the dose of physical activity; greater insight into the potential mechanisms underlying physical activity induced improvements in cognition may be provided by utilizing a fixed dose of physical activity in comparison to different types of control conditions to isolate those characteristics that improve cognition to the greatest extent.

### 2.3. What are suitable assessments of cognition for this research area?

In addition to considerations of appropriate research designs and control conditions, it is paramount that investigators assessing the after effects of acute bouts of physical activity on cognition use cognitive assessments that are appropriate for detecting the potentially small changes in performance that result from an intervention. That is, many historically popular cognitive assessments utilized within clinical or school-based neuropsychological evaluations were designed primarily for screening purposes (Chan, Shum, Toulopoulou, & Chen, 2008) and while effective at identifying large-scale impairments in cognition, they often lack sufficient sensitivity to detect changes in response to an intervention. While potentially advantageous from a clinical evaluation standpoint, many of these assessments also rely on subjective evaluations of behavior. When these assessments are utilized within the context of quantifying behavioral change in response to an intervention, it is essential that a great deal of care is provided towards ensuring that the subjective evaluator is blind to condition to prevent potential bias in their evaluations. Similarly, given the adaptable nature of cognition, it is particularly important that investigators utilize cognitive assessments that attempt to isolate the cognitive construct of interest. Cognitive assessments which rely upon a broad range of cognitive operations or which aim to provide a generalized index of a cognitive domain allow for a wide assortment of alternative strategies or compensatory processes to be utilized that may mask or misattribute the effects of these doses of physical activity.

Given the constraints imposed by proper research designs that necessarily entail some degree of repeated assessment of cognition, it is also essential that any cognitive assessment employed be designed for repeated testing. Many historically popular cognitive assessments were not designed for repeated testing, so once the participant has completed the task a single time they understand the nature of the task or adopt compensatory strategies — such as blurring vision during the Stroop task, resulting in drastically improved performance. With the growing emphasis across all areas of science on ensuring the validity and reliability of measures, tasks that exhibit these large shifts in performance across repeated exposures may be particularly problematic. That is, if the underlying cognitive processes necessary for the completion of a task or the cognitive strategies employed vary with repeated exposures, the validity and reliability of such an assessment is inherently compromised as the assessment may not consistently rely upon and measure the key cognitive construct of interest across repeated exposures (Cook & Beckman, 2006). In this sense, the construct validity of the assessment becomes compromised as the interpretation of performance on the assessment is attributable to different processes across repeated exposures (Fitzner, 2007).

Relatedly, it is also essential that any cognitive assessments employed are reliable in consistently assessing the construct of interest. With the growing availability of high-quality open-source stimulus presentation programs such as PsychoPy (Peirce, 2009), it is relatively easy to enable precise timing of behavioral responses and eliminate the need for manual timing approaches — thereby removing additional sources of variance in assessments. Further, a key characteristic of cognitive assessments that determines the reliability is the number of trials utilized in the assessment. Evidence from the motor control domain has demonstrated that the minimum number of trials necessary to reliably quantify reaction time is dependent upon the type of cognitive assessment, with 18 trials being sufficient for simple reaction time tasks whereas a two-choice reaction time task required a minimum of 30 correct trials (Hamsher & Benton, 1977). Cognitive assessments which provide an insufficient number of trials are particularly problematic psychometrically because it is not possible to determine if changes in performance reflect meaningful differences or are simply reflective of random fluctuations in behavior (Brown et al., 2014). Although the number of trials is only classically considered with regard to the reliability of reaction time measures, it also impacts the reliability of accuracy measures. With relatively few trials, analysis of variation in response accuracy may be confounded due to the greater weight each individual trial holds (e.g., a 10% difference in performance requires an error on only a single trial with 10 trials presented, while such a difference requires an error on 10 trials with 100 trials presented). However, while the reliability of the assessment is important, one of the most interesting aspects to cognitive systems is their dynamic, adaptable nature. Thus, cognitive assessments that provide very high levels of test-retest reliability may demonstrate reduced sensitivity for detecting more transient changes in cognition. Specifically, test-retest reliability refers to the capacity of a measure to consistently obtain the same results across different time points. While being robust against day-to-day variations in cognition is important for assessing trait-like characteristics, if performance on a task is highly consistent across repeated assessments then it is unlikely that the task will have sufficient sensitivity to detect more transient changes in performance in response to an intervention — such as following a single bout of physical activity.

Finally, although there is a growing trend to characterize reaction time based outcomes separate from response accuracy based outcomes (Ludyga et al., 2016; McMorris, 2016), it is important to acknowledge that the extent to which physical activity-induced improvements in cognition manifest within reaction time or accuracy outcomes may likely be dependent upon the task parameters or instructions. That is not to say that acute bouts of physical activity may not differentially impact the speed of responding relative to the ability to respond accurately, but rather that task parameters or instructions may constrain responding to enhance the likelihood for one parameter (i.e., reaction time or response accuracy) to manifest the changes in cognition. For instance, tasks that emphasize a high rate of responding through rapid stimulus presentations (i.e., short stimuli durations) and short intertrial intervals (i.e., less time between the onset of the first stimulus and the onset of the next stimulus) necessarily constrain reaction time and bias enhancements in cognition towards manifesting within response accuracy outcomes. Alternatively, tasks that provide long stimulus durations with plenty of time between each stimulus enable participants to take their time in responding accurately, effectively biasing improvements in cognition towards manifesting within reaction time outcomes. Further, as evidenced by Themanson, Pontifex, and Hillman (2008), even small differences in task instruction can lead to dramatic differences in the strategic approach participants employ. Ultimately then, to advance our understanding of the effects of single bouts of physical activity on cognition, it is important that investigators utilize cognitive assessments that are sufficiently sensitive and conceptually appropriate for detecting these more transient changes in cognition and pay particular attention to task parameters and instructions that may moderate the effect towards particular response outcomes.

### *2.4. How can violations of statistical power be avoided?*

In addition to many of the points of consideration discussed so far, it is equally paramount that investigators understand and employ a sample size that is sufficient to ensure their study is appropriately powered for their statistical analysis. Most statistical training focuses on the concept of controlling for the probability of *finding a difference* between conditions when *no difference is present* (i.e., Type I errors or false positive) by setting and correcting an appropriate alpha level (i.e., $p = 0.05$). Equally important is controlling for the probability of *finding no difference* between conditions when *a difference is present* (i.e., Type II errors or false negative). For instance, if a study finds an effect of physical activity for one aspect of cognition but not for the other, it may be that both aspects of cognition were influenced but that the study was not adequately powered to detect those differences. Power is simply the inverse of the probability of a Type II error and can be interpreted as reflecting the ability of a study to detect differences between conditions when such differences actually occur (Biau, Kernéis, & Porcher, 2008). At 80% power ($\beta = 0.8$), a study would be expected to observe an effect 80% of the time when the effect is present; conversely, it might fail to observe an effect — when the effect is present (Type II error) — 20% of the time. Stated more plainly, if some effect actually exists, 20 studies (out of 100) would be expected to report null findings. As the sample size directly influences the probability of committing a Type II error (Biau et al., 2008), it is imperative that investigators incorporate power analysis computations into the study preparation process to determine how many participants are necessary given their design. Further, in interpreting the literature, it is necessary to acknowledge that failing to observe a statistical difference between conditions does not necessarily mean that the effect is absent, but rather that the absence of a finding may relate to the magnitude of the effect and the sample size.

Accordingly, to better facilitate this understanding, future research should begin reporting sensitivity analysis of their research designs in the analysis sections. That is, rather than report how many participants a design requires given assumptions about the effect size — as done in the *a priori* power analysis, a sensitivity analysis indicates what effect sizes should be observable given the analytical strategy and number of participants employed. The benefit then is in not having to make assumptions about the magnitude of an effect, as instead the focus is on what the study is sufficiently powered to detect. For instance, a within-subjects, 2 (condition: physical activity vs control) × 2 (time: pretest vs posttest) repeated measures ANOVA design with 18 participants should be sufficiently powered to detect interactions at or above moderate effect sizes ($f = 0.25$ which translates to an approximate Cohen's $d = 0.5$) assuming alpha at 0.05, power at 80%, and a correlation among repeated measures of 0.75 (Faul, Erdfelder, Lang, & Buchner, 2007). Therefore, such a study should be sufficiently powered to find moderate or larger effect sizes but would be unlikely to observe smaller effect sizes — with the limitation that a false negative (lack of significance/null finding) might occur 20% of the time. The sensitivity of a study thus depends upon the number of comparisons, the number of participants, the tolerance for committing a Type II error, and the correlation between measures in repeated measures approaches.

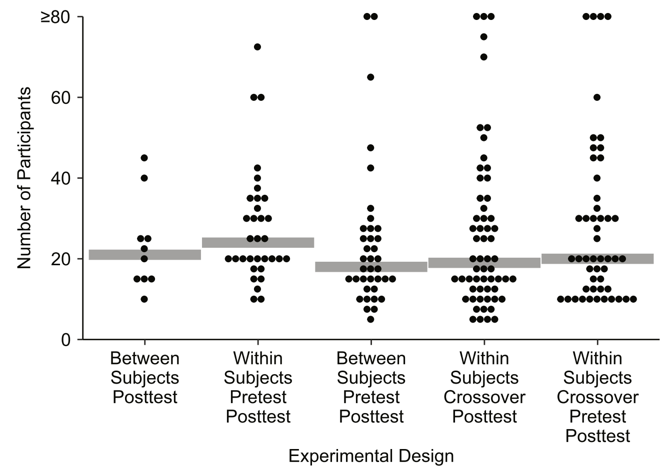


**Fig. 9.** Illustration of the sample size for each investigation within each research design. Note that values represent the number of participants within each group for between subject designs. Horizontal gray bars indicate the median sample size within each research design.

In order to provide some insight into the potential for violations of statistical power in the acute physical activity literature, the total number of participants included within analysis was extracted from each study. To provide greater conceptual/statistical similarity between the within and between-subjects designs, the total number of participants was extracted as the number of participants within each group for between subject designs. As evident in Fig. 9, across each of the various study designs, the median sample size utilized within the literature has been around 20 participants/participants within each group. Problematically, this means that roughly half of the published literature has utilized sample sizes below 20 participants. The underpowered nature of this body of literature does not necessarily compromise interpretation of the positive findings — as the false positive error rate is independent from the sample size assuming the samples are representative of the population as a whole (Biau et al., 2008). Rather, these trends towards insufficiently powered investigations call into question the extent to which the absence of an effect reflects true specificity of an effect associated with physical activity or simply was the result of insufficient power to detect changes in cognition. Although a growing number of investigations have made concerted efforts to improve in this regard, by continuing to conduct investigations inadequately powered for their design, we run the risk of developing misleading conclusions. Making standard the reporting of the sensitivity of the design employed has the potential to not only aid in the review process for publication and strengthen the literature base, but also to provide vital information to enhance the discussion of stable and/or inconsistent findings observed across research studies exploring the after effects of acute physical activity on cognition.

### *2.5. How can transparency and clarity of reporting be ensured?*

Beyond a call for greater statistical transparency, there is a growing emphasis for enhancing the transparency and clarity of reporting research findings. In particular, there is a growing emphasis that journals require longitudinal, randomized controlled trials to adhere to standardized guidelines for ensuring the transparency and quality of their reporting known as CONSORT (http://www.consort-statement.org; Altman, 1996). The idea behind these guidelines is to ensure that investigators take greater care in making sure that the research design and analysis are clearly articulated within the published literature. Although these guidelines are primarily aimed at longitudinal research, the core tenants remain applicable to acute physical activity investigations. Indeed, reporting on the flow of participants through a study such as illustrated in Fig. 10, would enhance readers'

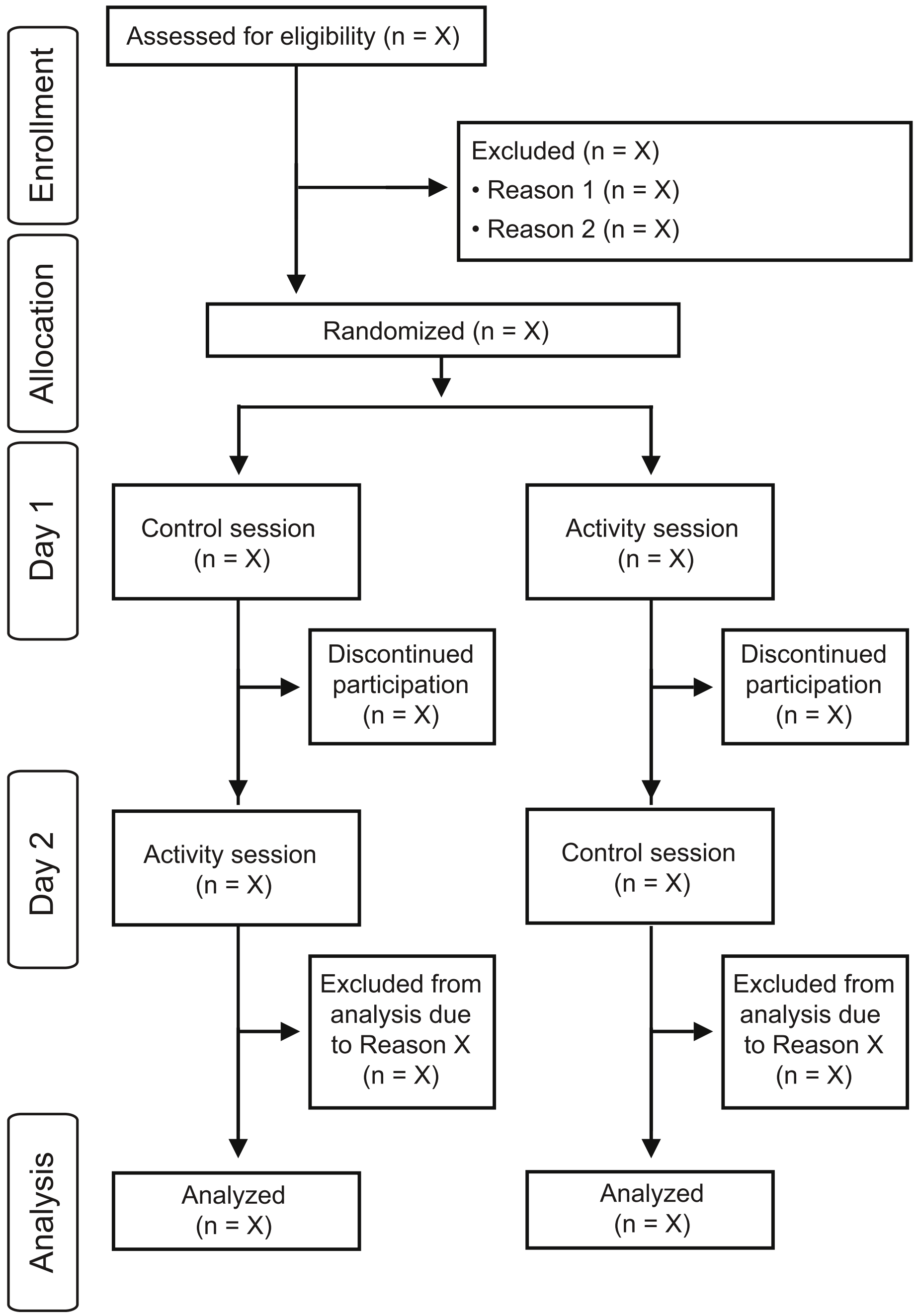


**Fig. 10.** Example of a CONSORT flowchart for a randomized within-subject crossover pretest posttest comparison acute physical activity design.

understanding of the study design as well as facilitate the transparency of where participants may have been lost between consent and analysis. This information is essential for ensuring that studies are free of bias and utilize representative participant populations. Similarly, other guidelines focus on reporting how the sample was determined, randomized, and powered for the analysis: all clearly applicable to work in this area. While adherence to CONSORT guidelines for acute physical activity investigations is voluntary to-date, adherence would greatly enhance the transparency and — hopefully — rigor of investigations in this area.

Similarly, there is a growing emphasis that investigators adhere to recommendations from the World Medical Association Declaration of Helsinki that research involving human subjects should be preregistered, even for studies that are not of a medical or clinical trial nature (Loder, Groves, & MacAuley, 2010; Williams, Tse, Harlan, & Zarin, 2010). Such emphasis builds upon the desire for greater transparency in the design, analysis, and disclosure of research studies as emphasized by CONSORT guidelines so as to also make transparent the intention of the research study (Miguel et al., 2014). By preregistering an investigation, researchers make more transparent the primary and subsequent outcomes of the research study — detailing information regarding the planned data collection, statistical approach, dependent and independent variables of interest, data transformations/coding, and *a priori* exclusion criteria to gain insight into the outcome of interest. In doing so, the hope is to achieve greater clarity between those analyses which were hypothesis driven and those which were exploratory, while at the same time minimizing the potential for unintentional ‘p-hacking’, ‘fishing’, or other undesirable research approaches such as not publishing findings from tasks which show unfavorable or null outcomes. Accordingly, a number of publicly accessible sites exist for researchers to preregister their studies, varying in the information they require and the extent to which they allow for the registration of observational investigations. Such sites include ResearchRegistry.com, AsPredicted.org, The Open Science Framework, ClinicalTrials.gov, the International Clinical Trials Registry Platform, ISRCTN registry, and the World Health Organization's Registry Network.

We also need to move beyond simple significance testing and begin reporting on the clinical relevance of our investigations. That is, while inferential statistical approaches provide key information regarding the probability of observing a given distribution in the data, ultimately such information boils down to a dichotomous decision to accept or reject the null hypothesis (Nakagawa & Cuthill, 2007; Wilkinson & the Task Force on Statistical Inference, APA Board of Scientific Affairs, 1999). Thus, classical significance testing provides little-to-no information regarding the clinical relevance of a finding. In this context, clinical relevance is inferred based upon the estimated magnitude of an effect (i.e, Cohen's d or correlation coefficient) (Nakagawa & Cuthill, 2007). Such information not only aids meta-analysis but also facilitates the comparison of improvements in cognition induced by physical activity against those induced by other interventions.

However, it is important that investigators utilize appropriate effect size calculations for their research designs. That is, the classic formula for computing Cohen's d for a sample (Cohen, 1977; Lakens, 2013) is given by:

$$d_s = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{(n_1-1)SD_1^2 + (n_2-1)SD_2^2}{n_1+n_2-2}}} = t\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

The use of the pooled standard deviation ultimately makes this formula only appropriate to utilize for between-subjects designs (Lakens, 2013). When used to calculate effect sizes for within-subjects repeated measures designs, the correlation between measures will lead to an overestimate of the effect size. Therefore, the repeated measures Cohen's d (Lakens, 2013) is more appropriate and is given by the formula below, where $r$ is the correlation between repeated measures:

$$d_{rm} = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{SD_1^2 + SD_2^2 - 2 \times r \times SD_1 \times SD_2}} \times \sqrt{2(1-r)} = t\sqrt{\frac{2(1-r)}{n}}$$

The use of the repeated measures Cohen's d — which accounts for the correlation between repeated measures — thus provides a more conservative estimate of the effect size while at the same time remains directly comparable to between-subjects calculations of Cohen's d for a sample. Consistent with the idea of increased transparency, the specific formula used within an investigation should be made clear by denoting the approach as a subscript, with $d_s$ indicating the classic Cohen's d for a between-subjects sample and $d_{rm}$ indicating the repeated measures Cohen's d (Lakens, 2013).

Beyond provision of effect size estimates, it is also important to report confidence intervals surrounding those effect sizes in order to provide the reader with a greater perspective on the precision of the effect size and the stability of effect sizes across multiple investigations (Cumming & Finch, 2001; Wilkinson & the Task Force on Statistical Inference, APA Board of Scientific Affairs, 1999). However, unlike confidence intervals surrounding means, confidence intervals surrounding standardized effect sizes rely upon noncentral distributions and therefore do not necessarily lend themselves towards presentation as a generic formula (Cumming & Finch, 2001). This is likely one reason they have not been commonly reported within the literature, despite calls for their inclusion for almost two decades (Wilkinson & the Task Force on Statistical Inference, APA Board of Scientific Affairs, 1999). In order to compute the confidence intervals surrounding an effect size, it is first necessary to determine the noncentrality parameters for the given confidence interval. This can relatively easily be computed in R (R Core Team, 2013) given the following code, where $t$ and $df$ are drawn from the $t$-test:

```
install.packages("MBESS"); library(MBESS)
ncp <- conf.limits.nct(ncp = t, df = df, conf.level = 0.95)
```

Using the resulting noncentrality parameters (ncp$Lower.Limit and ncp$Upper.Limit), the confidence interval surrounding the Cohen's d for a between subjects comparison (Kelley, 2007) is then calculated as:

$$\left(ncp\$Lower.\ Limit\sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \leq d_s \leq ncp\$Upper.\ Limit\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}\right)$$

Whereas the confidence interval for the repeated measures Cohen's d comparison (Kelley, 2007; Nakagawa & Cuthill, 2007) is calculated as:

$$\left(ncp\$Lower.\ Limit\sqrt{\frac{2(1-r)}{n}} \leq d_{rm} \leq ncp\$Upper.\ Limit\sqrt{\frac{2(1-r)}{n}}\right)$$

In each instance, the confidence interval is calculated using the $t$-test variant of the Cohen's d formula with the noncentrality upper and lower bounds used in place of the $t$-statistic. Post-hoc statistical reporting of both inferential statistics and measures of effect size, could then be reported together following a format such as: $t$(df) = X.X, $p$ = 0.X, $d_{rm}$ = X.X [95% CI: X.X to X.X]. Providing measures of the effect size even for nonsignificant differences further aids the reader in determining the extent to which the lack of a statistical difference may simply result because the effect size was smaller than what the investigation is powered to detect (which should be clearly evident based upon the sensitivity analysis included by the authors). Therefore, investigators should ensure that measures of effect size are reported alongside classic inferential statistics.

## 3. Conclusions

Collectively, the aim of the present review was to provide some initial discussion regarding key characteristics of the acute physical activity and cognition literature to highlight potential future directions and approaches for research. A central focus of the extant literature has been on how moderate to vigorous intensity aerobic activities lasting 16–35 min in duration impacts upon inhibitory control immediately following the cessation of the activity bout in young adult populations (18–34 years of age). Yet there remains a dearth of literature outside such a narrow focus. In order to continue to advance research in this area it is necessary to transition away from focusing only upon these parameters and examine the extent to which future investigations contribute towards the theoretical development of the field. A key consideration then is the underlying supposition for why these bouts of physical activity might induce changes in cognition, as well as the specificity of the effect to particular domains of cognition or populations. Overall, the field has progressed from focusing on low level cognitive processes towards examining the impacts on higher-order level cognition, namely cognitive control with a particular focus on inhibition. However, evidence elucidating the effects of acute bouts of physical activity on other domains of cognitive control (i.e., working memory and cognitive flexibility) and aspects of cognition (i.e., memory and intelligence/achievement tests) remains scarce.

Future research should also seek to inform on the mechanisms underlying the relationship between acute bouts of physical activity and cognition. While a preponderance of studies assess cognition immediately following single bouts of physical activity, we still have little understanding of the persistence of enhancements in cognition following the cessation of physical activity. Similarly, to progress the field towards a greater understanding of these relationships it is necessary to better characterize the dose of physical activity and consider the mechanistic justifications for why alterations in such characteristics might differentially induce changes in cognition. Such insights might contribute towards a greater understanding of how best to maximize the characteristics of physical activity to incur the greatest cognitive enhancements and the minimum dose necessary to induce such changes.

Finally, it is also essential that investigations in this area maintain a high degree of experimental rigor in their research approach. While it is important to emphasize that the nature of scientific investigation encourages the utilization of different experimental approaches and designs, with the growing focus on rigor and reproducibility within science it is important that investigators take greater care in justifying and clearly articulating their approach. Ultimately, while the extant literature suggests a positive association between acute bouts of physical activity and cognition, empirical evidence is still necessary to inform when, how, and for whom physical activity can be utilized to enhance cognition in a clinically relevant manner. Such research would thus better speak to the role of these acute bouts of physical activity for sustaining optimal levels of brain health.

## Conflicts of interest

The authors have no competing interests to declare.

## Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Appendix A. Supplementary data

A complete database of studies included in this review and their associated codings can be found at https://doi.org/10.1016/j.psychsport.2018.08.015.

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