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Physical activity for cognitive and mental health in youth

Citation for published version:
Lubans, D, Richards, J, Hillman, C, Faulkner, G, Beauchamp, M, Nilsson, M, Kelly, P, Smith, J, Raine, L & Biddle, S 2016, 'Physical activity for cognitive and mental health in youth: A systematic review of mechanisms' Pediatrics. DOI: 10.1542/peds.2016-1642

Digital Object Identifier (DOI):
10.1542/peds.2016-1642

Document Version:
Peer reviewed version

Published In:
Pediatrics

Physical Activity for Cognitive and Mental Health in Youth: A Systematic Review of Mechanisms

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Short title: Physical Activity for Cognitive and Mental Health

Financial Disclosure Statement: The authors have no financial relationships relevant to this article to disclose.

Funding Source: Funding for this review was provided by an Australian Research Council Future Fellowship Grant, FT 140100399.

Conflict of Interest Statement: Potential Conflicts of Interest: The authors have no conflicts of interest relevant to this article to disclose.

Review registration: Protocol registered with the International Prospective Register of Systematic Reviews (PROSPERO 2015:CRD42015024116).

Abbreviations: CNS – central nervous system; BDNF – brain-derived neurotrophic factor; IGF-1– insulin-like growth factor 1; VEGF – vascular endothelial growth factor; MRI – magnetic resonance imaging; fMRI– functional magnetic resonance imaging; CONSORT – consolidated standards or reporting trials; PE – physical education; PRISMA – preferred reporting items for systematic reviews and meta-analyses; RCT – randomized controlled trial; WHO – World Health Organization.

Contributors' Statements:

David R. Lubans: Dr Lubans was responsible for the study design and conceptualization, literature search, extraction of data, interpretation of findings and drafting and editing the final manuscript. In addition, Dr Lubans was responsible for the design of the conceptual model and associated figure included in the manuscript.

Justin Richards**:** Dr Richards was involved in the study design and conceptualization, literature search, extraction of data, interpretation of results, and drafting and editing the final manuscript.

Charles H. Hillman: Dr Hillman contributed to the data interpretation, and writing and revision of the sections regarding cognition and brain. Dr Hillman also provided general revision and commentary to the entire manuscript.

Guy Faulkner: Dr Faulkner contributed to the study design and conceptualization, interpretation of results, contributing to drafts and editing the manuscript.

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Paul Kelly: Dr Kelly contributed to the study design and conceptualization, interpretation of results, contributing to drafts and editing the manuscript.

Jordan J. Smith: Dr Smith conducted the risk of bias assessment for included studies. In addition, Dr Smith was involved in the interpretation of findings and drafting and editing of the final manuscript.

Lauren Raine: Dr Raine contributed to the drafting of the cognition and brain sections of the manuscript, as well as the interpretation of the results. She also provided general revision and commentary to the entire manuscript.

Stuart J. H. Biddle: Dr Biddle contributed to the study design and conceptualization, interpretation of results, and drafting and editing of the final manuscript.

ABSTRACT

Context: Physical activity can improve cognitive and mental health, but the underlying mechanisms have not been established.

Objective: To present a conceptual model for explaining the mechanisms responsible for the effect of physical activity on cognitive and mental health outcomes in young people and conduct a systematic review of the evidence.

Data sources: Six electronic databases (Pubmed, Psychinfo, SCOPUS, Ovid Medline, SportDiscus, and Embase).

Study selection: School-, home- or community-based physical activity intervention or laboratory-based exercise interventions. Studies were eligible if they reported statistical analyses of changes in i) cognition or mental health and ii) neurobiological, psychosocial, and behavioral mechanisms.

Data extraction: Data relating to methodology, assessment period, participant characteristics, intervention- type, setting, facilitator/delivery were extracted.

Results: Twenty-five articles reporting the results from 22 unique studies were included in the final systematic review. Mechanisms studied were: neurobiological (*n*=6 studies), psychosocial (*n*=18), and behavioral (*n*=2). Significant changes in at least one potential neurobiological mechanism was reported in five studies, and significant effects for at least one cognitive outcome was also found in five studies. One of two studies reported a significant effect for self-regulation, but neither study reported a significant impact on mental health.

Limitations: Small number of studies and high levels of study heterogeneity.

Conclusions: The strongest evidence was found for improvements in physical self-perceptions, which accompanied enhanced self-esteem in the majority of studies measuring these outcomes. Few studies examined neurobiological and behavioral mechanisms and we were unable to draw conclusions regarding their role in enhancing cognitive and mental health.

INTRODUCTION

The World Health Organization (WHO) defines mental health as a state of well-being and effective functioning in which an individual realizes his or her own abilities, is resilient to the stresses of life and is able to make a positive contribution to his or her community. [1] Cognitive function, defined as mental processes that contribute to perception, memory, intellect, and action, provides a core foundation upon which mental health (both well-being and ill-being) is established. [2] There is conceptual overlap among common indicators of well-being, which commonly include constructs of global self-esteem, subjective well-being, quality of life and psychological resilience. For the purpose of this review, the term ill-being will be used to represent pre-clinical psychological states and clinically diagnosed mental health disorders (see Supplementary Table 1 for definitions).

Childhood and adolescence represents a period of rapid growth and development characterized by neuronal plasticity, [3] formulation of self-concept, [4] and the establishment of behavioral patterns that may enhance or diminish mental health. [5] This may be a critical period for improving mental health, and the delivery of physical activity interventions might be one way of achieving such improvements. [6] Although there may be a bi-directional relationship between physical activity and mental health, experimental studies conducted with youth have demonstrated that increasing physical activity has small but positive effects on a range of cognitive and mental health outcomes. [6-9] Despite an increasing number of experimental studies reporting the cognitive and mental health benefits of participating in physical activity, the underlying mechanisms responsible for the positive effects have not been established. [10-12]

The ability to explain how and under what conditions mental health changes occur may facilitate the delivery of successful interventions. Therefore, the aims of this paper are to: i) present a conceptual model for explaining the effects of physical activity on cognitive and mental health outcomes in young people, and ii) conduct a systematic review of physical activity interventions that have examined the impact on mental health outcomes and potential mechanisms in child and adolescent populations. The conceptual model includes three broad potential mechanisms (i.e., neurobiological, psychosocial and behavioral), which are summarized in Figure 1 and explained below.

Neurobiological mechanisms

The neurobiological mechanism hypothesis proposes that participation in physical activity enhances cognition and mental health via changes in the structural and functional make-up of the brain. [13,14] In a recent review, Voss and colleagues [15] identified three broad categories of neurobiological mechanisms responsible for cognitive functioning, involving changes in the central nervous system (CNS): (i) *cells, molecules and circuits* that, with current scientific techniques, are only detectable in animal studies (e.g., neurogenesis), (ii) *biomarkers* (e.g., grey matter volume, cerebral blood volume and flow), and (iii) *peripheral biomarkers* (e.g., circulating growth factors and inflammatory markers) that can be observed in humans.

Neuroimaging techniques (e.g., magnetic resonance imaging [MRI], functional magnetic resonance imaging [fMRI] and event related brain potentials) have been used to identify structural and functional mechanisms that may explain the relationship between physical activity, cardio-respiratory fitness and cognition. [16] Such techniques do not provide a direct measure of mechanism change; instead, they represent the outcome of some other mechanistic change in the brain that is not directly measurable in human subjects. The animal literature has identified a number of mechanistic examples (e.g., changes in brain-derived neurotrophic factor [BDNF]). Research in rodents has indicated that running increases cell proliferation, survival, and differentiation. [17] Furthermore, exercise stimulates the growth of new capillaries, which are critical for the transport of nutrients to neurons [18]. BDNF, insulin-like growth factor 1 (IGF-1), and vascular endothelial growth factor (VEGF) are neurochemicals that increase with exercise and facilitate the downstream effects of cardio-respiratory exercise on brain structure, function, and cognition. [19] These neurochemicals are highly concentrated within the hippocampus, as well as various other brain regions. [20] There is also evidence for the benefits of cardio-respiratory fitness on the structure of the brain's cortical (e.g., frontal lobes, anterior cingulate) and subcortical regions (e.g., hippocampus, basal ganglia). [21,22]

There may also be neurobiological explanations for the effects of physical activity on well-being and ill-being, through the release of endogenous opioids and their interaction with other neuro-transmitter systems. [14] Participation in physical activity is thought to lead to the release of endorphins, which can ease pain and produce a feeling of euphoria. [14] However, there is little empirical evidence to support this assertion in adults [14] or children. [23] It is not known if the short-term pleasure that individuals experience during physical activity is due to endorphins and to what extent this contributes to improved mental health in young people over time. The 'feel good' effect of activity may be due to changes in one or more brain monoamines, with the strongest evidence available for dopamine, noradrenaline, and serotonin. [13]

Psychosocial mechanisms

Drawing upon both hedonic [24] and eudemonic [25,26] perspectives (see Supplementary Table 1), physical activity has the potential to improve well-being via a range of psychosocial mechanisms. Several theoretical frameworks propose that well-being is achieved by satisfying basic psychological needs for social connectedness, autonomy, self-acceptance, environmental mastery, and purpose in life. [27,28] Our psychosocial mechanism hypothesis recognizes that physical activity provides an opportunity for social interaction (relatedness), mastery in the physical domain (self-efficacy and perceived competence), improvements in appearance self-perceptions (e.g., body image) and independence (autonomy). In addition, physical activity can facilitate interaction with the natural environment [29]and potentially improve mood, which may impact upon wider affective states and other indicators of well-being.

Consistent with existing theoretical models [30,31] participation in physical activity may lead to improved task self-efficacy in one's ability to perform specific activities, which generalize first to broader perceived physical self-concept and then to global self-esteem. However, physical activity may also have a negative impact on mental health outcomes among children and adolescents in certain contexts and circumstances. [32,33] For example, poorly designed and delivered physical education lessons may thwart students' needs satisfaction and lead to decreases in perceived competence and global self-esteem. Similarly, participation in physical activity may also influence physical self-perceptions within the appearance sub-domain (e.g., perceived attractiveness and body image). [34]

Short-term experimental studies have demonstrated promising effects on self-reported well-being immediately following exercise in natural environments, which are not seen following the same exercise indoors. [29] These findings are grounded in the theory that humans are biologically predisposed to be attracted to nature and have spent the majority of their evolutionary history in natural environments. [35] Among adults, connectedness to nature has been found to be positively associated with mental health outcomes. [36] In addition, the restorative properties of natural environments may explain why participation in physical activity in natural environments has mental health benefits. [37,38]

Behavioral mechanisms

The behavioral mechanism hypothesis proposes that changes in mental health outcomes resulting from physical activity are mediated by changes in relevant and associated behaviors. In particular, participation in physical activity may improve sleep duration, sleep efficiency, [39,40] sleep onset latency[41] and reduce sleepiness. [42] In addition, participation in physical activity programs may also influence self-regulation and coping skills that have subsequent implications for mental health.

Participation in physical activity is recommended for the management of adolescents suffering from sleepiness and fatigue. [43] While the majority of studies reporting a relationship between sleep-related outcomes and physical activity have been cross-sectional, it is plausible to suggest that increasing energy expenditure through activity may influence sleep patterns, which may, in turn, improve mental health outcomes. Of note, a recent systematic review and meta-analysis concluded that insufficient sleep was associated with deficits in higher-order and complex cognitive functions and an increase in behavioral problems in children. [44]

Participation in physical activity provides an opportunity for the development of self-regulation and coping skills that may influence mental health. For example, yoga is a holistic system of multiple mind-body practices for mental and physical health that includes relaxation practices, cultivation of awareness/mindfulness, and meditation [45] that help to develop coping skills. A systematic review concluded that yoga may have utility for treating anxiety or anxiety related disorders in child and adolescent populations. [46] The development of self-regulation and coping skills promoted in recreational activities such as yoga and martial arts, may explain the positive effects of these activities on mental health. [46,47]

Summary of conceptual model

Numerous reviews have demonstrated the positive impact of physical activity on cognitive and mental health outcomes in child and adolescent populations [6,8,9] and a range of potential mechanisms have been described, [10-12] which we have summarized in our conceptual model in Figure 1.. To our knowledge, this is the first systematic review of the mechanisms responsible for the effects of physical activity on cognitive and mental health in young people.

METHODS

The conduct and reporting of this review adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-analysis statement (PRISMA). [48] The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO 2015:CRD42015024116).

Study eligibility criteria

1. *Types of participants:* Participants were school-age (5 to 18 years) at baseline. Studies targeting populations with learning difficulties, cognitive deficits and developmental disorders were not included.
2. *Types of interventions:* Any school-, home- or community-based physical activity intervention or laboratory-based exercise intervention. Obesity prevention or treatment interventions that included a dietary component were not eligible for inclusion.
3. *Types of mental health outcome measures:* Studies were included if they reported statistical analyses of changes in cognitive function or indicators of global well-being or ill-being.
4. *Types of potential mediators:* Studies were included if they reported statistical analyses of changes in potential neurobiological, psychosocial, and behavioral mechanisms.
5. *Types of study designs:* Study designs included experimental or quasi-experimental (i.e., non-random allocation of participants to groups) studies of at least one week in duration.

Information sources and search strategy

Six electronic databases (Pubmed, Psychinfo, SCOPUS, Ovid Medline, SportDiscus, and Embase) were searched from the year of their inception up to July, 2015 (Supplementary Table 2). An additional search of recently published systematic reviews examining the effects of physical activity on mental health outcomes was conducted and the reference list of all retrieved studies were reviewed.

Data extraction

Study data relating to methodology, assessment period, participant characteristics, intervention setting, intervention facilitator/delivery and intervention description were extracted and are reported in Supplementary Table 3.

Risk of bias assessment

Risk of bias was assessed using the Physiotherapy Evidence Database (PEDro) scale, [49] which consists of 11 separate items representing different sources of potential bias in scientific research (Supplementary Table 4).

RESULTS

Overview of studies

The flow of studies through the review process can be seen in Figure 2. Following the exclusion of duplicates, the initial database search yielded 7118 potentially relevant citations, of which 97 were retained for full-text review (Supplementary Table 3). From this phase, 18 articles satisfied the inclusion criteria and a further seven relevant articles were identified from the reference lists of included articles and hand searches. The studies were conducted in North

America (n = 12 in the U.S and n = 2 in Canada), Europe (n = 1 each in the U.K, Spain, Switzerland, Sweden, France, Norway and Portugal), Oceania (n = 3 in Australia), and Asia (n = 1 in China). In total, 20 studies used a randomized controlled trial (RCT) design (n = 5 cluster RCTs), whereas the remaining five studies used a non-randomized controlled design. The sample size for included studies ranged from n = 18 to n = 1273.

Risk of bias for included studies

Detailed information on the risk of bias for the included studies can be seen in Supplementary Table 4. In total, 12 (48%) studies satisfied fewer than half of the risk of bias criteria and six (24%) studies satisfied two thirds or more. The most consistently satisfied criteria were items (1) 'eligibility criteria' (80% of studies), and (10) 'between-group comparisons' (100% of studies), whereas the most poorly satisfied were items (5) 'blinded subjects' (0% of studies) and (6) 'blinded intervention facilitators' (0% of studies).

Neurobiological mechanisms

Six papers (3 unique studies) tested the effects of physical activity intervention on potential neurobiological mechanisms and cognitive outcomes (Table 1), all of which were RCTs. [7,22,50-53] The sample size for these studies ranged from n = 18 to n = 221, and studies exclusively targeted children (range = 7 to 11 years). A variety of potential neurobiological mechanisms were evaluated, but there was little overlap between studies and we were unable to conduct a meta-analysis. For example, included studies evaluated characteristics of brain structure and functioning across a variety of brain regions using MRI, fMRI, and electroencephalography

(EEG). The specific outcomes assessed within these studies also varied, but were all related to aspects of cognitive performance. Significant changes in at least one potential mechanism were reported in five (83%) studies, and effects for at least one cognitive outcome were also found in five studies. Four studies examined associations between changes in potential mechanisms and changes in mental health outcomes, and significant associations were found in two of these studies.

Psychosocial mechanisms

Eighteen studies examined the effects of physical activity interventions on psychosocial mechanisms and mental health outcomes, [54-71] of which 13 were RCTs and five were quasi-experimental trials (Table 2). Study sample sizes ranged from $n = 20$ to $n = 1273$ and studies targeted both children and adolescents. The most commonly evaluated psychosocial mechanisms were physical self-concept and physical self-perceptions (encompassing competence, appearance and fitness subdomains). A range of mental health outcomes were evaluated, with studies reporting the effects of the interventions on self-esteem, depression, quality of life, psychological well-being, vitality, general self-efficacy, and positive/ negative affect. Of the 18 studies, 12 (67%) reported a significant intervention effect for at least one potential mechanism, and 11 (61%) reported a significant intervention effect for at least one mental health outcome.

Behavioral mechanisms

Only two studies [56,72] evaluated the effects of interventions on behavioral mechanisms, and of these, only changes in self-regulation skills were assessed (e.g., self-control) (Table 3). One of the two studies [72] reported significant intervention effects for self-regulation, but neither study reported a significant impact on mental health.

DISCUSSION

Despite consensus that physical activity plays an important role in promoting optimal cognitive and mental health in young people, [73] little is known regarding the mechanisms by which this effect works. Through our systematic review, we mapped a range of *potential* mechanisms corresponding to neurobiological, psychosocial and behavioral hypotheses previously described. The strongest evidence was found for improvements in physical self-perceptions which accompanied enhanced self-esteem in the majority of studies measuring these outcomes. Few studies examined neurobiological (e.g., brain structure and functioning) and behavioral mechanisms (e.g., self-regulation) and due to study heterogeneity we were unable to draw firm conclusions regarding these mechanistic pathways.

Risk of bias summary

Overall, the risk of bias for included studies was mixed, with approximately half of studies failing to satisfy 50% or more of the criteria. While no studies blinded participants or intervention facilitators, it is important to recognize that these criteria are difficult to satisfy in the context of physical activity interventions. Perhaps more importantly, only one in five studies reporting blinding assessors during data collection. In physical activity trials, this is a common and meaningful source of bias, [74] which should be addressed in future research.

Neurobiological mechanisms

Experimental studies examining neurobiological mechanisms have emerged in the last five years and additional studies will emerge as technology becomes more available. Existing studies have investigated different aspects of the brain using a variety of methods (e.g., MRI, fMRI, EEG, ERP) and consequently, the effect of any specific brain-related mechanism on improved cognitive function remains unclear. Hillman et al. [7] found that a 9-month physical activity intervention aimed at improving cardio-respiratory fitness resulted in improved performance as well as increased attentional resources on tasks requiring increased inhibition and cognitive flexibility. Furthermore, Chaddock-Heyman and colleagues [50] found decreased fMRI activation of the right anterior prefrontal cortex, mirroring a more mature or adult-like activation pattern in a subsample of children participating in a physical activity intervention.

By contrast, changes in brain activation patterns did not correspond with between-group differences in cognitive control following an 8-month exercise trial with overweight children. [52] It is important to note that the study conducted by Davis and colleagues involved overweight/obese children and used the anticascade task, while the participants in the Hillman study were of a healthy weight status and a flanker task was used. Of note, these tests tap into different aspects of inhibitory control (perceptual interference vs. behavioral inhibition) and it is not clear that the two studies should corroborate one another.

Future studies should aim to replicate the findings of previous research and test the transferability of these findings into real world settings (e.g., schools). As none of the studies included in the review targeted adolescents, there is a strong rationale for examining neurobiological mediators in this population. Indeed, should clear evidence of the efficacy of physical activity programs for improving cognition become available, the question of timing will be a critical one for educators and physical activity researchers alike. Whether childhood or adolescence offers greater potential for improving cognitive functioning would clearly be of interest, and more experimental evidence from across the age spectrum would help to shed light on this question.

Psychosocial mechanisms

There was evidence for a causal link between physical self-perceptions and indicators of well-being (e.g., self-concept and self-esteem). Of note, changes in appearance self-perceptions coincided with improvements in self-esteem in five out of the six studies evaluating these constructs together. Similarly, improvements in physical self-concept and perceived competence coincided with improvements in self-esteem in two of three and three of four studies, respectively. These findings are consistent with the predictions of the Exercise and Self-Esteem Model [30] and Shavelston's model of self-concept. [31] As previously described, improvements in specific physical self-perceptions (e.g., perceived sport competence) are hypothesized to generalize to improvements in overall physical self-concept and ultimately to enhanced self-esteem. According to the theory, improvements in self-esteem should be expected in the presence of positive changes in self-perceptions or self-concept.

Encouragingly, this is what was observed in the majority of these studies. In one study, [59] the effect of an aerobic exercise intervention on depressive symptoms among overweight children was partially mediated by changes in perceived appearance and global self-worth. This study suggests that perceptions of the self are indeed related to ill-being in youth.

Connectedness with others is universally accepted as an important component of well-being, and this construct features prominently in current psychological theories. [24-26] In the studies included in this review, relatedness was often operationalized as 'social acceptance' (i.e., the belief that one is valued and accepted by others). Social acceptance was measured in three studies, [58,59,68] and each of these studies also examined the effects of interventions on self-esteem. Interestingly, significant intervention effects were reported for social acceptance in only one study [58] yet improvements in self-esteem were found for all three. Considering the recognized importance of this construct for wellbeing, this is perhaps a surprising finding. However, individuals can have strong feelings of social connectedness, and at the same time perceive themselves as physically unattractive and incompetent in sport and exercise settings. In such cases, these individuals would have little capacity to improve feelings of social acceptance through participation in a physical activity program.

Behavioral mechanisms

No relevant studies investigating sleep-related variables were identified through the search, highlighting a clear gap in the literature. Only two studies investigated the effects of interventions on self-regulation skills and the findings were mixed. For example, Lakes et al.

[72] reported positive effects on cognitive, affective and physical self-regulation skills following a 3-month school-based martial arts training intervention. Conversely, Laberge and colleagues [56] found no effect for self-control among underserved adolescents participating in a physical activity intervention targeting the school lunch hour. In addition, neither study reported positive effects for mental health indicators.

As illustrated, there is a clear lack of studies examining the effect of potential behavioral mechanisms on changes in mental health. It is plausible that the adoption of behavioral management strategies could assist young people to feel more in control, and hence more satisfied with their lives. Not included in our original search , but worthy of investigation, academic behaviors (distinct from academic performance), such as time on task [75] and homework completion may improve after participation in physical activity [73]. Additional behaviors, such as drug taking (e.g., smoking and alcohol), diet, recreational screen-time, and academic behaviors [73] may also mediate the effect of physical activity interventions on cognitive and mental health outcomes.

Limitations of the current review

A small number of studies satisfied our eligibility criteria and there was considerable heterogeneity among studies. It is likely that there are other neurobiological, psychosocial and behavioral variables not included within our conceptual model that might explain cognitive and mental health outcomes in young people. Therefore, our conceptual model should not be considered a complete picture, but rather an important starting point to be reconciled through future research. It is important to note that i) there may be a bi-directional relationship between physical activity and mental health, and ii) multiple independent mechanisms may influence mental health outcomes in parallel or via interaction with one another.

Summary of research recommendations

None of the studies included in this review examined potential mechanisms using an accepted statistical mediation analysis technique. [76] To enable robust meta-analyses, future studies should report standardized regression coefficients for (i) the effect of interventions on potential mechanisms, (ii) the effect of interventions on mental health outcomes, and (iii) the association between changes in potential mechanisms and changes in mental health outcomes. Researchers are encouraged to answer the following research questions and provide support for our conceptual model.

Neurobiological questions

- What are the specific brain structures/networks and cognitive functions most influenced by physical activity?
- How does varying the intensity of physical activity differentially alter the effects on brain structure and function?

Psychosocial questions

- How can the design and delivery of physical activity interventions be maximized to enhance their effect on physical self-perceptions?
- What is the relative importance of participant experience of the physical activity intervention and the physiological dose received?
- What is the role of social interaction in a physical activity context for affecting mental health?
- What influence does the natural environment have on enhancing the mental health benefits of physical activity for young people?

Behavioral questions

- What is the role of sleep as a mediator for the effect of physical activity on cognitive function, well-being and ill-being?
- What type of physical activity supports academic behaviors (e.g., time on task and homework completion) and subsequent cognitive development?
- Can improvements in motor skill proficiency enhance cognitive outcomes?

CONCLUSION

Systematic reviews and meta-analyses have demonstrated that physical activity interventions can improve cognitive and mental health in young people, but our review identified a lack of available evidence for the specific mechanisms responsible for these effects. However, our review has established that participation in physical activity can improve physical self-perceptions and enhance self-esteem in young people. Our findings highlight several important gaps in the research literature, and emphasize the need for more high quality experimental research to examine the specific paths of influence between physical activity participation and improved mental health. In particular, future studies should conduct statistical mediation analyses, using the conceptual model provided herein as a framework. Improving our understanding of how physical activity improves mental health in child and adolescent populations, may assist in the design of interventions to optimize their possible impact on these critically important outcomes. Finally, elucidating the mechanisms underpinning the effect of physical activity on cognition, well-being and ill-being may provide the necessary impetus for schools, governments and policy makers to prioritize physical activity promotion.

ACKNOWLEDGEMENTS

The authors would like to thank Natasha Whyte for her assistance in the retrieval of journal articles. Funding for this review was provided by an Australian Research Council Future Fellowship Grant, FT 140100399.

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Figure 1. Conceptual model for the effects of physical activity on mental health outcomes in children and adolescents

Figure 2. Flow of studies through the review process