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Exercise, sports, and performance arts benefit cognition via a common process. Tomporowski, Phillip D.; Pesce, Caterina; Psychological Bulletin, Vol 145(9), Sep, 2019 pp. 929-951. Publisher: American Psychological Association; [Journal Article] Abstract: Exercise training is widely promoted as a method to enhance both physical health and cognitive function. Although routine exercise engenders physiological adaptations to the body and brain, its effects on mental processing are uncertain. Our review of the experimental evidence reveals that acknowledging the role of skill acquisition may help clarify the exercise–cognition relation. Instructional methods that optimize physical and mental challenge provide the conditions necessary to produce long-term changes in the way individuals process information, make decisions, select movements, and experience the consequences of actions. Main conclusions drawn by intersecting theory-based research on the linkages between chronic exercise and cognitive function and research on the associations of both sport and performance arts with cognitive function are as follows: (1) Exercise may be but one of many types of movement activities that can benefit cognition; (2) the process of skill acquisition provides a parsimonious explanation for outcomes across exercise, sport, and performing art studies; (3) the allocation of mental resources required during skill acquisition, independently from or interactively with the level of physical energy expenditure, is essential for reaping the largest cognitive benefits; and (4) cognitive benefits obtained via skill-acquisition interventions are enduring. This review also highlights issues that call for future research to provide convergent evidence for the relation between skill training and cognition; the inclusion of outcome measures other than executive functions; and a naturalistic translational approach to complement controlled experiments in chronic exercise and cognition and skill learning research. (PsycINFO Database Record (c) 2019 APA, all rights reserved)

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Exercise, Sports, and Performance Arts Benefit Cognition Via a Common Process

By: Phillip D. Tomporowski
Department of Kinesiology, University of Georgia;
Caterina Pesce
Department of Movement, Human and Health Sciences, University of Rome "Foro Italico"
Acknowledgement:

Empirical support for the benefits of *exercise*, defined as a subset of physical activity planned and structured for training purposes (Caspersen, Powell, & Christenson, 1985), on human cognitive functioning began to amass in the late 1990s. Early studies reviewed in the 1980s (Tomporowski & Ellis, 1986) were still largely atheoretical and considered physical activity effects on cognition in an undifferentiated manner. At the threshold of the new millennium, a series of research reports (Kramer et al., 1999; Kramer, Hahn, & McAuley, 2000), a book chapter (Kramer et al., 2002), and a meta-analytic review of the literature (Colcombe & Kramer, 2003) suggested that routine aerobic exercise had a positive influence on older adults' cognitive function, specifically executive functioning (Kramer, Erickson, & Colcombe, 2006). These publications, together with emerging lines of neurophysiological research conducted with animals (Cotman & Berchtold, 2002; van Praag, Christie, Sejnowski, & Gage, 1999) and humans (Eriksson et al., 1998), led to a surge in research and public interest in the benefits of exercise on cognitive aging. In the mid-2000s, Spirduso, Poon, and Chodzko-Zajko (2008) proposed a model that highlighted various pathways by which exercise might favorably impact older adults' cognition (see Figure 1). In the model, *cognition* is defined broadly and encompasses learning, attention, executive function, problem solving, and information-processing speed. Physical activity (or exercise) is also defined widely and its various forms of bodily movement produced by skeletal muscles that result in energy expenditure (Caspersen et al., 1985), including exercise, are not differentiated. Exercise's influence on cognition was proposed to be either direct or mediated and moderated by a variety of factors. The direct effects of exercise on brain structures and functions were thought to induce neurological changes that impact cognition. Indirect effects were proposed to be meditated by such constructs as health status and physical and psychological resource availability. The strength of the relation between exercise and cognition was hypothesized to be influenced by moderators such as age, education, and genetics.

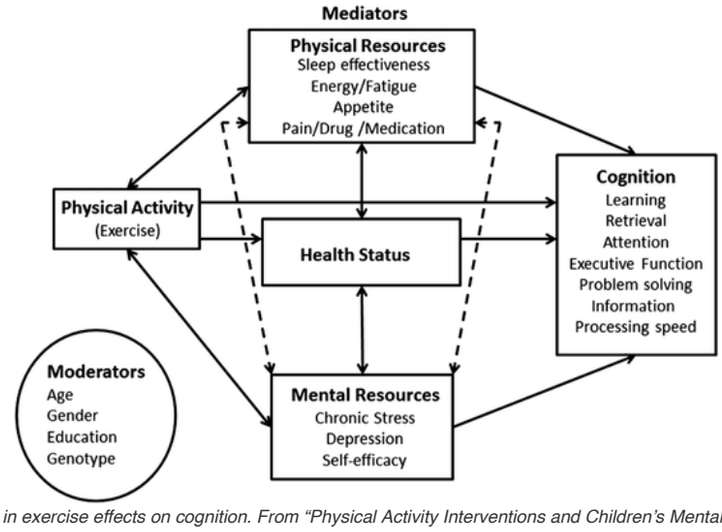

Figure 1. Working model of the role of mediators in exercise effects on cognition. From "Physical Activity Interventions and Children's Mental Function: An Introduction and Overview," by P. D. Tomporowski, K. Lambourne, and M. S. Okumura, Preventive Medicine, 52, pp. S3–S9. Copyright 2011 by Elsevier, Inc. Adapted with permission.

This model also influenced developmental researchers who were interested in interventions designed to benefit children's physical and mental functions (Tomporowski, Lambourne, & Okumura, 2011). Numerous studies employed chronic physical activity interventions that consisted of training regimens lasting weeks, months, or years. A consensus emerged that the effects of exercise on cognition were particularly impactful for individuals on the two ends of the life span continuum (Tomporowski, Davis, Miller, & Naglieri, 2008; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011).

Publications assessing the effects of exercise and, more broadly, physical activity interventions on cognition and brain health in humans have increased dramatically since the early 2000s. In view of this research trajectory, it is important for researchers to reach a consensus concerning conditions under which chronic physical activity will influence individuals' cognitive functions. Deriving a consensus is timely and important because physical activity and exercise training have come to be viewed over the last decade by national and international organizations as critical for health and wellness (Organization for Economic Co-operation and Development, 2016; Physical Activity Guidelines Advisory Committee, 2018; World Health Organization, 2010). Meanwhile, the general public increasingly believes that cognitive benefits can be derived from exercise interventions. The ensuing review examines hypotheses that have fueled physical activity and exercise research and introduces an additional explanation for the relation that may stimulate new lines of inquiry.

A number of narrative reviews, systematic literature reviews, and meta-analyses have been performed. We identified 72 reviews that targeted children, adolescents, and young and older adults, as well as a review-of-reviews (Biddle, Ciaccioni, Thomas, & Vergeer, 2018). Several of these were conducted by panels of experts at the request of national organizations (e.g., The American College of Sports Medicine [Donnelly et al., 2016]; the Centers for Disease Control and Prevention Healthy Aging Research Network, in cooperation with the National Association of Chronic Disease Directors [Snowden et al., 2011]) and large research groups (e.g., Singh et al., 2018). Conclusions range considerably, with some reviews supporting a causal relation between physical activity/exercise and cognition to those which, applying more restrictive criteria to distinguish between the outcomes of higher and lower quality studies, considered the results to be inconclusive (Diamond & Ling, 2018; Singh et al., 2018).

Three themes emerge from comments made by the researchers who conducted these reviews. The first is the paucity of well-designed controlled experiments. Indeed, in a Delphi analysis of responses obtained from 23 leading exercise–cognition researchers focusing on the exercise–cognition relation, the highest ranked response was the need to establish causality between physical activity and cognition and academic achievement (Singh et al., 2018). Second, reviewers noted that efforts to draw strong conclusions are hampered by the lack of clear descriptions of the interventions employed. Third, the type of exercise intervention matters. The pattern of results provided by both meta-analytic and narrative reviews suggests that multicomponent interventions, which emphasize the integration of physical and mental activity, produce the clearest evidence for the benefits of exercise on cognition.

We provide additional evidence that the type of exercise and methods of instruction may explain the lack of consistent findings. Although instructional methods are still largely unconsidered, insufficiently described, and seldom manipulated, exercise type has received attention in recent years. Table 1 provides summaries of the results of 13 systematic literature reviews and/or meta-analytic reviews of chronic exercise studies published since 2016 that focus on the effects of different types of exercise interventions. Listed for each review are the cognitive tasks selected, the types of exercise interventions employed, and a summary of the findings. When applicable, effect sizes and confidence intervals for individual comparisons are provided. Furthermore, separate effect sizes are reported when the outcomes of exercise interventions of interest were compared to multiple exercise or nonexercise control conditions. In total, the results of these reviews consistently support the added value of multicomponent interventions that are designed to be mentally engaging. A close examination of experiments cited in these reviews provide additional support for this general conclusion. Table 2 provides summaries of 24 experiments in which exercise intervention complexity was manipulated. Interventions used for exercise and control groups are described for each study. Studies are grouped on the basis of age, and the methodological quality of each study was judged via conventional methods. Almost all experiments reported added benefits of complex exercise interventions. Further, the superiority for complex interventions emerged as the quality of experiments increased. Questions remain, however. It is unclear whether the benefits of chronic exercise interventions are general or specific to underlying components of cognition. The ability to address these and other questions may be improved by determining why exercise type and methods of instruction consistently benefit cognition. We address these topics in some detail in the following sections.

Table 1
Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Study	Age (years)	Review type	Cognitive function category	Intervention type (no. of studies)	Effect size (CI)	Conclusions on the effects of different intervention types on cognitive performance
Alvarez-Bueno et al. (2017)	Children and adolescents (age range = 4–14 years)	SLR + MA	Nonexecutive Function (NEF) Executive function (EF): Working memory (WM) Attention/inhibition (A/I) Cognitive flexibility (CF) Higher level executive function (HEF)	Quantitatively enhanced physical activity (20)	Standardized mean difference score: NEF: .21 [.07, .35] WM: .28 [.04, .52] A/I: .14 [–.01, .28] CF: .19 [–.01, .38] HEF: .21 [.09, .34]	**Advantage for qualitative enrichment** The benefits of different types of PA interventions are moderated by the type of cognitive outcome. Largest effect of qualitatively enriched PA on selective A/I.
				Qualitatively enriched PA (9)	NEF: .48 [.06, .90] WM: –.03 [–.17, .11] **A/I: .49 [.05, .43]** CF: –.25 [–.60, .10] HEF: /	
				Enhanced and enriched PA (9)	NEF: / WM: .16 [–.23, .55] A/I: .30 [–.15, .74] CF: / HEF: –.07 [–.46, .33]	
Barha, Galea, Nagamatsu, Erickson, and Liu-Ambrose (2017)	Middle-aged and older adults (≥45 years)	SLR + MA	EF: Episodic memory (EM) Visuospatial ability (VSA) Verbal fluency (VF) Processing speed (PS) Global cognition (GC)	Aerobic training (AT) (18)	Hedge's *g*: EF: 2.06 [1.58, 2.55] EM: .04 [–.36, .45] VSA: .64 [.14, 1.15] VF: .35 [.20, .50] PS: .47 [.24, .70] GC: .86 [.24, 1.47]	**Advantage for multimodal training** The benefits of different types of PA interventions are moderated by the type of cognitive outcome. All types of training benefited EF and visuospatial ability, but only multimodal training benefited EM.
				Resistance training (RT) (7)	EF: .64 [.41, .87] EM: .07 [–.08, .22] VSA: .55 [.1, –.95] VF: .83 [–.87, 2.53] PS: / GC: –1.81 [–2.88, .75]	
				Multimodal (AE + RT) **training**, MT (12)	EF: .49 [.28, .71] **EM: .48 [.33, .64]** VSA: 1.00 [.67, 1.34] VF: .72 [.51, .94] PS: .65 [.40, .90] GC: 1.80 [1.41, 2.19]	
				AE + RT groups (1) RT + MT groups (1)		

Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Table 1 (*continued*)

Study	Age (years)	Review type	Cognitive function category	Intervention type (no. of studies)	Effect size (CI)	Conclusions on the effects of different intervention types on cognitive performance
Bruderer-Hofstetter, Rausch-Osthoff, Meichtry, Münzer, and Niedermann (2018)	Middle-aged and older adults (≥45 years)	SLR + MA	GC		Standardized mean difference score:	**Advantage for combined aerobic exercise and cognitive training** Aerobic exercise plus cognitive training was the best-ranked intervention with largest effect.
			Learning and memory EF	Aerobic training (1) **Aerobic + Cognitive Training** (1)	2.1 [–.87, 5.1] **3.0 [.06, 5.9]**	
			Complex attention	Aerobic + Resistance + Dual-Task Training (1)	–.42 [–4.4, 3.6]	
			Language	Stretching + Dual-Task training (1)	–.39 [–4.4, 3.7]	
			Perceptual–motor skill	Stretching + Cognitive training (1)	–.16 [–4.1, 4.0]	
				Dance (1)	.26 [–3.7, 4.3]	
				Exergaming (2)	.48 [–1.6, 2.5]	
				Balance training (1)	–.14 [–4.2, 3.9]	
				Tai Chi (1)	1.8 [–1.0, 4.6]	
				Multimodal training (1)	–.09 [–2.9, 2.8]	
				Multimodal + Cognitive training (1)	.42 [–2.4, 3.3]	
				Multimodal + Dual-Task training (1)	–.04 [–4.1, 4.0]	
de Greeff et al. (2018)	Children (range = 6–12 years)	MA	EF: Inhibition WM		Hedge's *g* (collapsed across cognitive outcome measures):	**Advantage for cognitively engaging PA** PA interventions that include cognitively challenging motor coordination and skill acquisition demands are more effective in improving cognitive performance (moderate to large effect) than aerobic PA alone (small to moderate effect).
			CF Attention: Selective Divided Sustained Academic performance: Mathematics Spelling Reading	Aerobic training **Cognitively engaging exercise training**	.29 [.13, .45] **.53 [.14, .92]**	
Diamond & Ling (2016)	Across lifespan	SLR	EF	Aerobic training Resistance training Martial arts Yoga		**Advantage for exercise interventions challenging executive function skills**. Aerobic exercise, or resistance training, without a cognitive component produces little or no executive function benefit. Interventions that challenge executive function skills to their limits benefit them.

Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Table 1 (*continued*)

Study	Age (years)	Review type	Cognitive function category	Intervention type (no. of studies)	Effect size (CI)	Conclusions on the effects of different intervention types on cognitive performance

Gheysen et al. (2018)	Older adults (≥65 years)	SLR + MA	Memory Attention EF VSA PS Language GC	Combined Physical + Cognitive (PA + CA): Sequential PA + CA (9) **Simultaneous PA + CA** (29: 12 dual-task exercises, 6 exergames, 5 dance, 2 karate, 2 Tai Chi, 1 Exergame + Tai Chi) Sequential and simultaneous PA + CA (3) Comparison groups: No activity PA only (aerobic, strength training, combined AT + ST, stretching) CA only	Hedge's *g* (collapsed across cognitive outcome measures): .11 [–.10, .33] **.38 [.21, .55]** .32 [.19, .44] .16 [.04, .28] –.02 [–.21, .17]	**Advantage for combined physical plus cognitive training**. Combined physical and cognitive activity benefits cognition more than no activity or PA alone, but not more than cognitive training alone. Largest effects for interventions that integrate the cognitive challenges into the PA tasks.
Joubert & Chainay (2018)	Older adults (≥60 years)	SLR	EF WM GC	Combined physical and cognitive training (8) Physical vs. cognitive training (3) Physical training only (aerobic, resistance, coordination) (10)		**Undifferentiated** Various types of physical training (aerobic, resistance, coordinative) seem all able to benefit cognition, but complementarily enhancing different cognitive functions (moderation effect by cognitive outcome). The superiority of combined cognitive and physical training, though arguable from individual studies, does not allow definitive conclusions.
Lauenroth, Ioannidis, and Teichmann (2016)	Across lifespan	SLR	Attention (alertness, selective, divided) EF WM EM Learning ability Reasoning ability VF PS	Combined Physical + Cognitive (PA + CA): Sequential PA + CA (7) (aerobic; balance; strength and balance; flexibility & coordination; aerobic, strength & balance) Simultaneous PA + CA dual-task training (13) (aerobic; aerobic, strength, balance; multitasking exercises)		**Advantage for combined physical plus cognitive training** Combined physical and cognitive training, either simultaneously or subsequently, benefits cognitive function more than single PA. The level of task difficulty matters in determining cognitive performance gains.

Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Table 1 (*continued*)

Study	Age (years)	Review type	Cognitive function category	Intervention type (no. of studies)	Effect size (CI)	Conclusions on the effects of different intervention types on cognitive performance
Levin, Netz, and Ziv (2017)	Older adults (≥65 years)	SLR	Inhibition WM CF Dual-task cost Attention VSA Reasoning ability VF Language Learning Memory recall PS	Combined Physical + Cognitive (PA + CA): Sequential PA + CA (3) Simultaneous PA + CA dual-task training (6) (aerobic and resistance PA) PA only: One training type (4) (aerobic, resistance, balance, dance); Multiple training types (5) (aerobic & resistance).		**Advantage for combined physical plus cognitive training or multimodal physical training**. Combining different types of physical training or combining physical and cognitive tasks benefits cognitive function more than single PA.
Northey, Cherbuin, Pumpa, Smee, and Rattray (2018)	Middle-aged and older adults (≥50 years)	SLR + MA	GC Attention EF Memory WM	PA interventions: Aerobic training (18) Resistance training (13) Multicomponent training (10) **Tai Chi** (4) Yoga (2) Comparison groups: No activity; Low-intensity PA as stretching; Educational activity; Social activity	Standardized mean difference score: .24 [.10, .37] .29 [.13, .44] .33 [.14, .53] **.52 [.32, .71]** .13 [–.04, .36]	**Advantage for mindfulness activity** Largest benefits to cognition for a mindfulness activity requiring both motor and mental skills (Tai Chi). However, caution is warranted because of the small number of studies. Various types of physical training (aerobic, resistance, multicomponent, Tai Chi) seem able to benefit cognition. The effects are moderated by the type of cognitive outcomes; most pronounced effects of resistance training on memory and executive function.
Saez de Asteasu et al. (2017)	Older adults (≥65 years)	SLR	WM VF Attention PS	PA interventions: Aerobic training (11) Resistance training (3) Multicomponent training (Aerobic + Resistance + Balance and/or Flexibility) (3) Comparisons groups: Stretching/toning No exercise active control No intervention		**Advantage for multicomponent training** The review failed to support any cognitive benefits associated with aerobic exercise training but found suggestive evidence for beneficial effects of progressive resistance training. Multicomponent exercise training may have the most positive effects on cognitive function in aging, as it shows wide-ranging benefits to executive attention, VF and GC.

Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Table 1 (*continued*)

Study	Age (years)	Review type	Cognitive function category	Intervention type (no. of studies)	Effect size (CI)	Conclusions on the effects of different intervention types on cognitive performance
Vazou, Pesce, Lakes, and Smiley-Oyen (2016)	Children and adolescents (range = 4–16 years)	MA	Inhibition WM CF Planning Executive attention Creativity Reasoning Fluid intelligence Memory recall VSA PS	Aerobic (7) Motor skill (4) CE (2) Aerobic and motor skills (2) Aerobic and CE (8) Motor skill and CE (7) Aerobic, motor skills, and CE (1) Comparisons: Aerobic **Aerobic & CE** Motor skills; CE; motor skills and CE; motor skills and aerobic	Standardized mean difference score: .vs nonactive academics: .57 [.16, .98] .vs traditional PE: −.08 [−.38, .22]: .vs nonactive academics: **.69 [.031, 1.08]** .vs traditional PE: .17 [–.12, .47] .vs traditional PE: .21 [–.07, .48]	**Advantage for combined aerobic exercise and cognitive training**. As compared with nonactive academics, aerobic exercise interventions benefit cognition, but more pronouncedly when combined with cognitive challenges.
Zhu, Yin, Lang, He, and Li (2016)	Older adults (≥65 years)	MA	Memory Attention EF	**Combined Physical + Cognitive (PA + CA):** Sequential PA + CA (14) Simultaneous PA + CA (6, of which four dual-task training and two exergame with cognitive	Standardized mean difference score: .vs control group: **.29 [.12, .46]** .vs PA: **.22 [.06, .38]** .vs cognitive training: .06 [–.12, .25]	**Advantage for combined physical plus cognitive training**. Combined physical and cognitive activity benefits cognition more than no activity or PA alone. Lack of evidence for superiority of combined training when compared with cognitive training alone.

		challenge)
	PS	Comparison groups (PA only):
	VSA	Aerobic (6)
	Overall cognition	Strength/balance (1)
	GC	Exergames (one 3 with low cognitive challenge)
	Everyday cognition	Multicomponent training (12, all involving aerobic)

Note. Relevant findings and conclusions are highlighted in boldface type. CA = cognitive activity; CE = cognitively engaging; CI = confidence interval; CF = cognitive flexibility; EF = executive function; EM = episodic memory; GC = global cognition; PA = physical activity; PS = processing speed; VF = verbal fluency; VSA = visuospatial ability; WM = working memory.

Selected Systematic Literature Reviews (SLRs) and Meta-Analyses (MAs) of Chronic Exercise Studies Comparing the Cognitive Outcomes of Qualitatively Different Types of PA Interventions (Publication Years 2016–2018)

Table 2
Selected Primary Studies With Two or More Active Groups, Whose Level of Motor and/or Cognitive Involvement was Deliberately Designed or Manipulated

Study	Review source	Age range (in years)	Manipulation of mental involvement in the intervention (IG) and comparison group (CG)	Effects on cognition (Effect size [ES])	Quality (score, scale)
			Children and Adolescents		
Gallotta et al. (2015)	Alvarez-Bueno et al., 2017 de Greeff et al., 2018	8–11	One session/week, 5-month curricular physical education (PE) IG: PE focused on improving coordination and dexterity with a multisports approach and increasing task complexity Active CG: Traditional PE focused on health and social goals	**In favor of mental involvement** (Small to medium ES)	3/10 (Low) (PEDro)
Lakes et al. (2013)	Alvarez-Bueno et al., 2017	10–11	Five sessions/week, 9-month curricular PE IG: Focused on Taekwondo techniques (Two of five sessions/week) taught with emphasis on discipline and self-regulation Active CG: Evidence-based PE curriculum to address the Presidential Core Fitness Guidelines	**In favor of mental involvement** (Large ES)	2/5 (Low) (Jadad)
Koutsandréou, Wegner, Niemann, and Budde (2016)	Alvarez-Bueno et al., 2017 de Greeff et al., 2018	9–10	Three sessions/week, 10-week afterschool physical activity (PA) IG: Highly variable, motor-demanding after-school PA program, designed to be challenging to prevent automation Active CG: Cardiovascular exercise program Nonactive control group; assisted homework	**In favor of mental involvement** (Large ES)	5/10 (Fair) (PEDro) 2/5 (Low) (Jadad)
Mavilidi et al. (2015)	Alvarez-Bueno et al., 2017	4–5	Three sessions/week, 10-week afterschool PA IG: Integrated PA—enacting words through bodily movements Active CG1: PA unrelated to the learning task Active CG2: Gesturing to learn words seated Nonactive CG3: Verbal word learning seated	**In favor of mental involvement** (Medium ES)	2/5 (Low) (Jadad)
Pesce et al. (2013)	Alvarez-Bueno et al., 2017	5–10	One session/week, 6-month curricular PE IG: Specialist-led PA games designed to challenge executive function by instructional principles as contextual interference Active CG1: Specialist-led PA games Active CG2: Generalist-led traditional PE	**In favor of mental involvement** (Small ES), moderated by motor development status	3/5 (High) (Jadad)
Pesce et al. (2016)	Alvarez-Bueno et al., 2017	5–10	One session/week, 6-month curricular PE IG: Specialist-led PA games designed to address fitness, coordination, cognition and life skills goals, with special focus on joint stimulation of cognitive and motor functions Active CG1: Generalist-led traditional PE	**In favor of mental involvement** (Small ES), mediated by motor coordination outcomes	3/5 (High) (Jadad)

Selected Primary Studies With Two or More Active Groups, Whose Level of Motor and/or Cognitive Involvement was Deliberately Designed or Manipulated
Table 2 (*continued*)

Study	Review source	Age range (in years)	Manipulation of mental involvement in the intervention (IG) and comparison group (CG)	Effects on cognition (Effect size [ES])	Quality (score, scale)
Schmidt, Jäger, Egger, Roebers, and Conzelmann (2015)	Alvarez-Bueno et al., 2017 de Greeff et al., 2018		One session/week, 6-month curricular PE IG: PE with high physical exertion and high cognitive engagement (team games); focus on coordination and control Active CG1: PE with high aerobic physical exertion but low cognitive engagement (circuit training) Low-active CG2: Traditional PE with both low physical exertion and low cognitive engagement	**In favor of mental involvement** (Large ES)	6/10 (High) (PEDro) 3/5 (High) (Jadad)
			Middle-aged and older adults		
Ansai & Rebelatto (2015)	Barha et al., 2017	≥80	Three sessions/week, 16-week training program IG: Multicomponent (aerobic, strength, balance) training with increasing movement complexity and dual tasking Active CG1: Resistance training (repetitions' sets) Nonactive CG2: No intervention.	**No effects**	21/26 (High) (CONSORT)
Berryman et al. (2014)	Barha et al., 2017 Levin et al., 2017	60–85	Three sessions/week, 8-week training program IG1: Lower Body Strength (circuit with stations) + Aerobic (low and high intensity interval) Training IG2: Upper Body Strength + Aerobic Training Active CG: Gross motor activities: locomotor and object-control skills trained in isolation or combined	**Similar effects of physical fitness and motor skill training** (Small ES)	17/26 (Fair) (CONSORT)
Eggenberger, Schumacher, Angst, Theill, and de Bruin (2015)	Gheysen et al., 2018	>70	Two sessions/week, 6-month training program IG1: Interactive virtual reality video game dancing with simultaneous attention and motor coordination demands IG2: Treadmill walking with simultaneous memory training Active CG: Treadmill walking only	**In favor of mental involvement** with benefits maintained at 1-year follow-up (Small ES)	Weak (EPHPP)
Falbo, Condello, Capranica, Forte, and Pesce (2016)	Gheysen et al., 2018 Levin et al., 2017	65–80	Two sessions/week, 12-week training program IG: Physical-cognitive dual-task (DT) training designed to challenge core executive functions in a gross-motor fashion Active CG: Single-task (ST) coordination and balance training	**In favor of mental involvement** (Large ES)	Strong (EPHPP)
Hamacher et al. (2016)	Bruderer-Hofstetter et al., 2018 Levin et al., 2017	67 ± 3	Two sessions/week, 8-week training program IG: Dancing: focused on practicing coordination, learning specific dancing skills and switching between them, with progressive increase in coordinative demands. Active CG: health-related exercise composed of aerobic, strength and flexibility training.	**In favor of mental involvement** (Medium ES)	2/6 (Low) (GRADE)

Selected Primary Studies With Two or More Active Groups, Whose Level of Motor and/or Cognitive Involvement was Deliberately Designed or Manipulated
Table 2 (*continued*)

Study	Review source	Age range (in years)	Manipulation of mental involvement in the intervention (IG) and comparison group (CG)	Effects on cognition (Effect size [ES])	Quality (score, scale)

Hiyamizu et al. (2012)	Gheysen et al., 2018	>65	Two sessions/week, 12-week training program IG: Balance training performed simultaneously with calculations, visual searches, and verbal fluency tasks Active CG: Balance/strength training without concurrent tasks	**In favor of mental involvement** (Large ES)	Strong (EPHPP)
Leon et al. (2015)	Barha et al., 2017 Gheysen et al., 2018 Levin et al., 2017	61–84	Two sessions/week, 12-week training program IG: Integrated Physical + Cognitive Training with Challenge Incrementing (as number of stimulus–motor skill associations) Active CG: Same physical (aerobic and strength) training but without concurrent cognitive tasks	**In favor of mental involvement** (ES not indicated)	14/26 (Fair) (CONSORT)
Merom et al. (2016)	Gheysen et al., 2018	≥60	Two sessions/week, 8-month training program IG: Ballroom dancing progressive in motor complexity Active CG: Home walking program and optional biweekly group-based walking in local community park	**In favor of mental involvement**, selective outcomes (Small ES)	Moderate (EPHPP)
Mortimer et al. (2012)	Barha et al., 2017	60–79	40 weeks, number of weekly sessions not indicated IG: Tai Chi plus calisthenics, balance, and flexibility training Active CG: Brisk walking and stretching Social CG: Social interaction Nonactive CG: no intervention	**In favor of mental involvement** and, secondarily, of social activity (ES not indicated)	15/26 (Fair) (CONSORT)
Müller et al. (2017)	Gheysen et al., 2018	63–80	One to two sessions/week, 18-month training program IG: Dance involving learning of new movement sequences and coordinating movements under precision and time constraints CG: Strength/endurance training with mainly repetitive exercises and low demands of coordination and memory.	**Similar effects of physical fitness and motor skill training** (Medium to Large ES)	Moderate (EPHPP)
Sato, Seko, Hashitomi, Sengoku, and Nomura (2015)	Gheysen et al., 2018	≥65	40 weeks, number of weekly sessions not indicated IG: Cognitive water-based exercise designed to improve cognition with dual- and multiple-task walking in water Active CG: Normal water-based exercise: walking, strength and stepping exercise, stretching and relaxation in water.	**In favor of mental involvement** (ES not indicated)	Moderate (EPHPP)
Schättin, Arner, Gennaro, and de Bruin (2016)	Gheysen et al., 2018	≥65	24 sessions, three sessions/week, 8–10-week-training program IG: Exergaming with feedback to individually adjust task difficulty and variability of practice to enhance transfer Active CG: Repetitive static/dynamic balance training on stable and unstable surfaces with progression in difficulty	**In favor of mental involvement,** with a larger number of positive outcomes (ES not indicated)	Moderate (EPHPP)

Selected Primary Studies With Two or More Active Groups, Whose Level of Motor and/or Cognitive Involvement was Deliberately Designed or Manipulated

Table 2 (*continued*)

Study	Review source	Age range (in years)	Manipulation of mental involvement in the intervention (IG) and comparison group (CG)	Effects on cognition (Effect size [ES])	Quality (score, scale)
Taylor-Piliae et al. (2010)	Barha et al., 2017 Gheysen et al., 2018	≥60	Four to five sessions/week, 12-month training program IG: Tai-Chi with progressive learning of new postures and practice of progressively longer posture sequences Active CG: Western exercise: endurance, resistance/strength, and flexibility exercises, incremental Nonactive CG: Healthy aging classes	**In favor of mental involvement**, selective outcomes (Medium to Large ES)	17/26 (Fair) (CONSORT) Weak (EPHPP)
Witte, Kropf, Darius, Emmermacher, and Böckelmann (2016)	Gheysen et al., 2018	63–83	Two sessions/week, 5-month training program IG: Karate challenging interlimb coordination, strength, balance; attention, learning and memory in attack/respond Active CG: Fitness training challenging strength, balance, coordination reaction, rhythm and body awareness Nonactive CG: No intervention	**In favor of mental involvement**, selective outcomes (Small ES)	Moderate (EPHPP)
Wongcharoen, Sungkarat, Munkhetvit, Lugade, and Silsupadol (2017)	Bruderer-Hofstetter et al., 2018	≥65	Three sessions/week, 8-week training program IG: Simultaneously combined motor (Balance + Object Control) and cognitive training with variable task prioritization Active CG: Balance/locomotor and object control skills training in single and motor–motor dual-task fashion Cognitive CG: Cognitive and executive function training	**Similar effects of interventions with low .vs high mental involvement** (Medium ES).	3/6 (Moderate) (GRADE)
Yamada, Aoyama, Tanaka, Nagai, and Ichihashi (2011)	Levin et al., 2017	≥65	One session/week, 24-week training program IG: Aerobic, strength, and flexibility training in form of seated stepping exercise in dual task conditions (verbal fluency task). Active CG: Aerobic, strength, and flexibility training in form of seated stepping exercise in single task conditions	**In favor of mental involvement** (ES not indicated)	3/5 (High) (Jadad)
Yokoyama et al. (2015)	Gheysen et al., 2018	>65	Three sessions/week, 12-week training program IG: Fine-motor and flexibility training; aerobic and resistance training with concurrent cognitive tasks as arithmetic tasks Active CG: Fine-motor, flexibility, aerobic, resistance training	**In favor of mental involvement**, with a larger number of positive outcomes (ES not indicated)	3/6 (Moderate) (GRADE)

Note. PEDro = Physiotherapy Evidence Database; Jadad = Oxford Quality Scoring System; CONSORT = Consolidate Standards of Reporting Trials; EPHPP = Effective Public Health Practice Project; GRADE = Grading of Recommendations Assessment, Development, and Evaluation.

Selected Primary Studies With Two or More Active Groups, Whose Level of Motor and/or Cognitive Involvement was Deliberately Designed or Manipulated

The Importance of Exercise Type in the Exercise–Cognition Relation

Studies designed to assess the effects of chronic exercise training can be differentiated into two broad categories: those that adhere to a quantitative approach with experiments designed to identify the proper "dose" of exercise needed to produce desirable cognitive outcomes and those that take a qualitative approach and manipulate interventions in terms of type of exercise and its related complexity (Pesce, 2012). The quantitative approach to exercise effects on cognition parallels approaches promoted by the health and wellness "Exercise is Medicine" community, which considers the frequency, intensity, time, and type principle as the guideline for exercise prescription. Chronic exercise training designed specifically to alter components of physical fitness (i.e., cardiovascular function, muscular strength, muscular endurance, and flexibility) typically results not only in somatic adaptations (Porcari, Bryant, & Comana, 2015) but also in changes in brain structure and function (Voss et al., 2013) at multiple levels (e.g., molecular, cellular, neural network, and structure; Stillman, Cohen, Lehman, & Erickson, 2016). The majority of published chronic exercise and cognition experiments adhere to this approach and typically employ aerobic exercise training regimens designed specifically to improve cardiovascular fitness. The selection of the intensity, duration, and frequency of exercise was influenced by research conducted by exercise physiologists (American College of Sports Medicine, 2000). Aerobic exercise training is assumed to lead to brain adaptations that presumably underlie cognitive processing (Hillman, Erickson, & Kramer, 2008). Evidence of angiogenesis and improved vascularization was offered as support of the benefits of aerobic exercise (Churchill et al., 2002). Additional brain-based hypotheses have been proposed. They focus on neuromodulators that control the neural circuitry in brain regions involved in information processing, decision making and planning as underlying mechanisms. Likewise, the role of brain-derived neurotrophic growth factors is viewed as a potential candidate to explain the exercise–cognition relation (Szuhany, Bugatti, & Otto, 2015; Zoladz & Pilc, 2010). Despite these neuropsychological advances, clear and consistent behavioral evidence for a causal relation between chronic physical activity and cognition provided by narrative or meta-analytic reviews is lacking.

Researchers following the qualitative approach develop exercise interventions that combine physical activity—typically aerobic exercise—with motor or cognitive tasks that elicit varying levels of cognitive control and effort (Pesce, 2012; M. Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015; Tomporowski, McCullick, Pendleton, & Pesce, 2015). Some interventions are designed specifically to engage participants' executive functions; typically, via game-like conditions that require information processing and working memory to perform successfully. The initiation and control of actions and the flexibility to modify those actions based on environmental conditions are believed to strengthen component processes of executive function and memory storage (Diamond & Lee, 2011; Diamond & Ling, 2016; Tomporowski et al., 2015). Other interventions emphasize action–perception couplings that are hypothesized to instantiate knowledge through movement as a sort of "cognitive side effects of movement" (Paas & Sweller, 2012; Pesce, Croce, et al., 2016). The connection between physical movements and mental representations is fundamental to the perspective of embodied cognition (Beilock & Goldin-Meadow, 2010; Moreau & Tomporowski, 2018). Proponents of this view of learning suggest that sensorimotor experiences, regardless of their intensity, are linked to cognitive processes that underlie complex problem solving and strategy utilization (Beilock & Goldin-Meadow, 2010; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012) and play a role in shaping and maintaining knowledge (Barsalou, 2008; Gallese & Sinigaglia, 2011; Glenberg, 2010). The relevance of embodied cognition to the understanding of exercise effects on cognition is highlighted in a narrative review that intersects these two lines of research (Mavilidi et al., 2018). Central to this research approach is the quest to identify the features and mixture of exercise activities needed to produce desirable cognitive outcomes.

Quantitative and qualitative research approaches provide complementary methods of gathering information concerning the effects of exercise on cognition. Each approach is based on strong theoretical rationales that lend themselves to specific, testable hypotheses. In the main, conclusions of narrative and meta-analytic reviews suggest that the effects of fitness-centered exercise interventions reflecting the quantitative approach are relatively weak when compared with those obtained by more complex multicomponent interventions reflecting the qualitative approach, which emphasize mental engagement (Diamond & Ling, 2016), but the discussion is still ongoing (Diamond & Ling, 2018; Hillman, McAuley, Erickson, Liu-Ambrose, & Kramer, 2018). The current debate concerning the types of physical activities that enhance cognition may be resolved with a formal scientific strategy. The following sections propose a skill-acquisition approach to evaluating the exercise–cognition relation that focuses on skill development as a proximal outcome and skill-based training as interventions. This approach may provide a parsimonious explanation not only for the wide variation in results obtained in previous exercise experiments but also for the results obtained from studies conducted in nonexercise fields of research such as sports and the performance arts (see Figure 2). Sport has a unique position between physical exercise and performance arts. Sports training is, as exercise, a subset of physical activity that leads to physical fitness gains. Although fitness development or maintenance is the main aim of physical exercise and skill acquisition is only supportive to fitness objectives, the reverse holds for sports, whose main aim is developing expert performance with fitness development playing a supportive role to performance objectives. Skill acquisition and the development of expertise represent the main commonality between sports and performance arts, even though they may largely diverge in their physical fitness requirements. Looking at the role of cognitive engagement in exercise and sport, Pesce (2012) called for research at the intersection point between chronic exercise and sport expertise research. The present article goes beyond the boundaries of exercise and sport sciences to point to the role of skill acquisition.

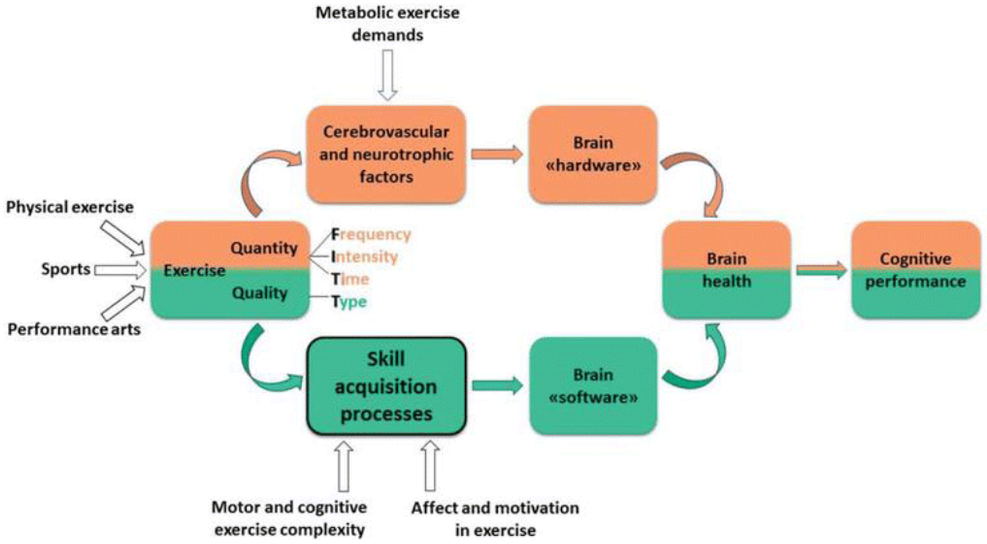

Figure 2. Hypothesized mediating roles of exercise demands and the process of skill acquisition on brain health and cognitive performance.

The Skill Acquisition Approach to the Exercise–Cognition Relation

The importance of skill acquisition developed over the course of exercise interventions designed to enhance cognition has been voiced intermittently over last decades. Tomporowski (1997) suggested that skill acquisition developed over extended training periods might be a common mechanism to explain cognitive benefits that older adults derive from both aerobic exercise and cognitive training. Hertzog and his colleagues (Hertzog, Kramer, Wilson, & Lindenberger, 2008) voiced a similar view of skill development after conducting a comprehensive review of longitudinal interventions designed to benefit older adults' cognitive function and to delay the onset of cognitive decline. More recently, Diamond and Ling (2016, in press) suggested that skills acquired during enrichment interventions may engender psychological benefits that may play a more instrumental role in developing and enhancing executive functions than physiological adaptations to exercise. Although the role of skill development has been voiced, it is understudied by exercise researchers and has seldom been addressed in contemporary reviews. As substantial theory-based advances have been made recently in the field of motor behavior, the processes involved in skill learning will be described in some detail, particularly when they relate to understanding the exercise–cognition relation.

Skill has been defined in a variety of ways; it is viewed here as "the ability to use one's knowledge effectively and readily in executing performance" (Tomporowski, 2003, pp. 1–2). Skill acquisition has been studied extensively, and the theoretical consensus is that change in learning proceeds via a stage-like process along a negatively accelerating performance curve (Ackerman, 1987; Fitts & Posner, 1967; Proctor, Reeve, & Weeks, 1990). The schema theory of motor control and learning (R. A. Schmidt, 1975) holds that during an initial stage of learning, novices are faced with understanding task requirements and selecting movements (cognitive stage). Once a general understanding of task demands is established, learners engage in repetitive practice designed to associate movements in concert with the environmental context and timing requirements (associative stage). The culmination of skilled acquisition is seen when movements become progressively more refined and are performed automatically with limited attentional control (autonomous stage). Throughout the skill acquisition stages, executive processes of working memory, response inhibition, and attentional switching are drawn upon. In addition, with practice and experience, individuals acquire increasingly more complex knowledge about the skill itself and the context in which skills can be deployed. Memories of past experiences can be used to determine the ways in which movements can be adapted strategically to meet specific environmental demands and challenges. Together, the repetitive use of the component executive functions and the storage of declarative knowledge provide the basis for expertise.

Newell and Rosenbloom (1981) proposed the power law of practice, which posits that a predictable relation exists between practice and skilled performance and that it applies across motor, psychomotor, and cognitive skills domains. Adherence to practice schedules over protracted periods has been used to explain the emergence of experts in domains such as sports, music, and academics. The trajectory of skill acquisition, however, can be influenced greatly by teaching methods. Pedagogical methods focus on the roles of instruction, modeling, guidance, and feedback in skill learning. Skill learning demands an individual's attention to task, mental engagement, and willingness to allocate physical and mental resources. Teachers are taught to use methods such as goal setting, reinforcement, verbal persuasion, and, most importantly, how to vary practice conditions in ways that challenge the learner's self-efficacy (McMorris, 2014).

Presently, the psychological changes that take place as learners acquire implicit movement control (procedural skill) and explicit declarative knowledge during the course of exercise interventions are seldom, if ever, taken into consideration in publications examining the chronic exercise–cognition relation. On the other hand, most research designed to address task-complexity hypotheses have used sequential or dual-task interventions that often remain unchanged over the course of the study. In both cases, very little information is provided to address the fidelity of the interventions. It may be that differences between experiments reporting evidence for the cognitive benefits of physical activity and those experiments showing weak or null effects are due to the presence of skilled instructors who used highly effective teaching methods to create challenging learning contexts that promote mental engagement and the motivation to learn and master new skills (Pesce et al., 2013; Pesce, Masci, et al., 2016; M. Schmidt et al., 2015; Vazou & Smiley-Oyen, 2014).The following sections delve into the field of motor behavior and instructional methods designed to challenge learners in ways that optimize learning. Motor behavior researchers have made strides in conceptualizing task challenge and its linkage to cognitive, affective, and motivational factors that differentially influence performance and skill learning. These advances have direct relevance for understanding how the presentation and implementation of exercise interventions may have differentially affected the results obtained from studies conducted to assess the exercise–cognition relation.

Cognitive Factors Involved in Skill Acquisition

The optimal challenge framework introduced by Guadagnoli and Lee (2004) isolates two interrelated factors hypothesized to contribute to skill acquisition: *Nominal difficulty*, which reflects the characteristics of the task to be learned, and *functional difficulty*, which reflects the skills of the performer and the environmental conditions in which performance occurs. The framework is founded on the assumption that motor learning is a goal-oriented, problem-solving process that depends on the utilization of information available during and following behavior. Guadagnoli and Lee (2004) and others (K. M. Newell, 1986) draw support for the importance of instructional contexts that create a balance between nominal and functional difficulty from research conducted on the contextual-interference effect, the role of augmented feedback, and the impact of task constraints on learning.

The contextual-interference effect is observed when instructional conditions that depress performance during practice produce more learning when measured on delayed tests of retention (Tomporowski, McCullick, & Horvat, 2010). Initial demonstrations of the effect were observed in associative-learning experiments that revealed the transfer of knowledge to new conditions depended greatly on the context of initial training (Battig, 1966). Learning was more robust when training occurred under conditions that varied from trial to trial than when conditions remained fixed and predictable. More recently, contemporary motor-learning researchers have shown how alterations in instructional context during practice sessions affect skill retention and transfer of learning. A number of studies have revealed that individuals who practice skills under varied training conditions (i.e., actions are varied across practice trials) perform initially more poorly than those who practice skills under constant training conditions (i.e., actions remain constant across practice trials); however, during retention or transfer tasks, those trained under varied learning conditions evidence superior performance (Merbah & Meulemans, 2011; Shea & Morgan, 1979). Similarly, augmented feedback, which is information that adds to that which is intrinsically available to an individual during skill acquisition, can have a marked effect on motor learning. A group of findings shows that delayed, distributed, or summarized augmented feedback depresses practice performance under specific instructional conditions but results in better learning (Lauber & Keller, 2014; Lee, Swinnen, & Serrien, 1994; R. A. Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2019).

From a different perspective (Corbetta & Vereijken, 1999; Latash, 2010), skill learning is conceived as a problem-solving task. Although repetition is inherently necessary for learning, what is repeated and how it is repeated matters as well. Each repetition during practice is an attempt to solve a movement problem. Once skills are stabilized in the form of optimally attainable synergies, further practice allows the learner to discover new relevant constraints that shape the emergence and stabilization of movement skills (K. M. Newell, 1986). Such new constraints may become increasingly relevant when moving from initial to advanced stages of motor skill acquisition (Latash, 2010; Renshaw, Chow, Davids, & Hammond, 2010). In this context, the "repetition-without repetition" principle means that the search for new solutions may weaken originally stabilized synergies as the learner vacillates between stability and flexibility (Pesce, Croce, et al., 2016). Variation between stability and flexibility in motor skill learning is central to the instructional methods. Indeed, the balance between repetition and change must be finely tuned to the learner's increasing skill level. Variability of practice methodologies enhance not only skill learning, but also motor creativity (Orth, van der Kamp, Memmert, & Savelsberg, 2017), cognitive development (Pesce, Croce, et al., 2016), exercise motivation, and fundamental need satisfaction (Sylvester, Curran, Standage, Sabiston, & Beauchamp, 2018).

To summarize, contextual interference, augmented feedback, and "repetition without repetition" promote learning gains under specific conditions. These gains can be linked to specific instructional methods that are modified by teachers to match a learner's constantly changing optimal challenge point. Individuals' successful adjustments to changing challenge points requires cognitive processing; that is, information processing, executive function, and long-term memory storage. Thus, even though given physical activities may be similar in terms of the metabolic demands and motor skills involved, the way the skills are taught may have largely different impacts on general mental effort and specific cognitive processes.

Affective and Motivation Factors Involved in Skill Acquisition

Skilled movement is experienced by some individuals as pleasurable, regardless whether one is a carpenter honing a section of wood or a golfer whose swing launches a ball from the tee. Positive psychology focuses on the affective responses experienced when one moves skillfully (Csikszentmihalyi, 1990). It is the physical act, as opposed to the consequences of the action, that is viewed to be the initiator of the pleasurable experience, termed by some as a flow state (Csikszentmihalyi, 2000). Achieving the psychological flow experience is hypothesized to depend on contexts in which the challenge imposed by a task matches an individual's skill level. According to flow theory, a difficult task given to an unskilled individual causes anxiety, and a simple task given to a skilled person promotes boredom.

Although seldom emphasized by motor-learning theorists, changes in training conditions alter individuals' affective states and impact motivation (Lewthwaite & Wulf, 2010). Recently, Wulf and Lewthwaite (2016) proposed the optimizing performance through intrinsic motivation and attention for learning (OPTIMAL) theory, which focuses on the interrelation of cognitive and affective processes that occur during skill acquisition. Drawing on the long linage of theories that have focused on the concept of the self (Bandura, 1997; Deci & Ryan, 1985), the OPTIMAL theory focuses on psychological variables that influence motor-skill learning. Two variables of particular interest to the present discussion are participant performance expectancies and learner autonomy. Performance expectancies are predictive beliefs about what is to occur in the future. Expectancies are typically described in terms of self-efficacy, which determine individual's goal setting and to self-regulated behaviors that prospectively lead to desired outcomes (Bandura, 1977; Locke & Latham, 2006). Performance expectancies have been shown to be affected by a variety of instructional context variables (e.g., positive feedback, modeling, and social-comparative feedback). Numerous studies have demonstrated that a participant's performance expectancies affect both motor performance and learning (Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015).

Similarly, learner autonomy, which is an individual's need to play a role in determining his or her behavior, also impacts motor-skill performance and learning. Approaches to learning that focus on how students can become self-regulated learners have been applied to motor skill learning in the physical education and sports context (Kolovelonis, Goudas, Hassandra, & Dermitzaki, 2012). Self-regulated learning involves cognitive, metacognitive, motivational, affective and volitional processes (Efklides, 2011). It is a component of motor skill learning that potentially underlies differential physical exercise's effects on cognition. The importance of perceiving that one has control over his or her environment has long been considered to contribute to human motivation (Eitam, Kennedy, & Tory Higgins, 2013). Instructional contexts that provide learners a choice in their actions during practice sessions have consistently been found to enhance motor learning. These improvements have been explained in terms of increased task-related mental engagement and deep processing (Chen & Singer, 1992; McCombs, 1989), self-regulation strategies (Kirschbaum, 1984), and motivation to learn (Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012). Variables as subtle as the way in which task instructions are worded can influence motor learning. For example, providing a learner with instructions that create a sense of choice for the learner led to superior learning of a modified cricket bowling movement (Hooyman, Wulf, & Lewthwaite, 2014).

In summary, skill acquisition clearly is not a simple undertaking. It is a complex phenomenon that involves an amalgam of cognitive, affective, and motivational processes that change as individuals proceed through the stages of learning. Many exercise and cognition researchers fail to consider the fact that exercise training programs require participants to acquire specific motor-movement skills. Regardless of the tasks selected for exercise interventions, participants are provided instruction, modeling, and guidance concerning how to move their bodies in specific ways, and augmented feedback is provided during and following training trials. Some interventions may be relatively simple, such as walking on a treadmill, whereas others may be considerably complex, such as leaping over hurdles. Some interventions may be performed individually while others involve skill learning in social interaction or even cooperative learning contexts that have been suggested to be responsible for outcome differences between studies of exercise effects on cognition (Best, 2012). And there is another important consideration: the rate of skill acquisition is task dependent. Some simple tasks can be mastered within a single training session; others can take weeks, months, or years to acquire. An important implication follows: Depending on the task's challenge and its modification across training sessions, participants' allocation of mental resources during exercise interventions can vary considerably. In the next section, experiments are reviewed that have manipulated task demand and challenge in line with recommendations made above. Unique to these studies is the emphasis on sport-like skills.

Designed Exercise and Sport Training Interventions

Recently, researchers have begun to examine closely the synergy that exists between sport activities and skill training. Moreau and his colleagues (Moreau & Conway, 2014; Moreau, Morrison, & Conway, 2015) proposed that cognitive gains are best obtained when training emphasizes complexity, novelty, and diversity. A series of studies that employed designed sport training contexts provides evidence that bolster their views. Moreau and his colleagues (Moreau et al., 2015), for example, in the context of an instructional, modeling, and trial-and-error problem solving training environment, placed emphasis on sensory processing that required participants to attend selectively to proprioceptive, kinesthetic, and visual information; motor-movements that differed in level of complexity; and problem solving that taxed working memory processes. The level of physical and mental challenge systematically increased over the course of 24 sessions conducted over 8 weeks of training. Variations in training demands were designed to promote adaptation to novel conditions that required controlled processing and mental engagement. Particularly important to the present paper were cognitive intervention outcomes showing that the sport training program benefited spatial ability and working memory capacity, despite that training involved motor movement challenges and testing involved numerical and verbal items, whereas traditional aerobic training did not. The designed sport concept developed by Moreau draws upon embodied cognition views of learning which emphasize the role of bodily movement when one interacts with changing environmental conditions. Linkages between movements and cognition have been made not only for sports (Beilock, 2008; Moreau & Conway, 2013), but also for language comprehension (Holt & Beilock, 2006), science learning (Kontra, Lyons, Fischer, & Beilock, 2015), and children's academics (McClelland, Pitt, & Stein, 2016). This allows one to hypothesize the centrality of skill learning in relating cognition to performance in several domains.

Similarly, Pesce (2012) introduced the gross-motor cognitive training which emphasizes the role of movement complexity during physical activity training. Focusing on neurological evidence for a relation between the prefrontal cortex and the cerebellum, Pesce and Ben-Soussan (2016) proposed that combining complex motor skills with physical activity during physical education classes would have an additive effect on the development of children's executive functions. Pesce and her colleagues (Pesce, Masci, et al., 2016) conducted a large clustered randomized control trial with 920 young children that contrasted the effects of 6 months of weekly physical education games that emphasized variability of practice and contextual interference with traditional physical education instruction. Only children who participated in the combined physical education and motor skill training condition exhibited improvements in inhibitory control. Mediational analyses revealed that intervention effects on ball control benefited children's inhibitory control and suggested to the researchers that visuomotor experiences initially challenged and then honed interceptive and planning processes.

A randomized controlled experiment by Lakes and her colleagues (2013) conducted with seventh grade children assessed the impact of a 9-month martial arts (Taekwondo) training program on executive functions and compared it with standard physical education instruction. Instruction followed a scaffolding procedure in which a highly ranked master instructor first introduced a few movements (e.g., a series of blocks and strikes) and provided guidance and feedback. As skill progressed, additional and more challenging movement sequences were introduced and practiced. The entire Taekwondo form comprised 36 different movements that followed specific directional patterns. Performance purportedly required planning, self-monitoring, and self-evaluation. Skill level was rated, and improvements were recognized by belt color, which signaled the introduction of longer and more complex forms. Children assigned to standardized physical education classes included stretching, running, and exposure to various sports and games. Processes of working memory, inhibitory control, and cognitive flexibility after the intervention were better for children trained in martial arts compared to those receiving traditional physical education.

These studies, though limited in number, support predictions made herein and conclusions drawn by Diamond and Ling (in press), who proposed the following central characteristics for interventions that favorably impact executive functions: (a) practice conditions that continuously challenge executive function processes, (b) selection of learning tasks that elicit commitment and emotional investment, (c) instructional environments that include supportive instructors, and (d) performance that leads to feelings of competence and self-confidence." We noted in our review of controlled experiments conducted with older adults that several studies employed exercise interventions based on martial arts and dance. The learning of stylized, complex series of movements found in karate (Witte, Kropf, Darius, Emmermacher, & Böckelmann, 2016), Tai Chi (Mortimer et al., 2012; Taylor-Piliae et al., 2010), and social dance (Eggenberger, Schumacher, Angst, Theill, & de Bruin, 2015; Hamacher, Hamacher, Rehfeld, & Schega, 2016; Merom et al., 2016; Muller et al., 2017) exemplify the types of interventions, methods of instruction, and social context that may be critical for deriving cognitive benefits.

Although sport training and competition play immense roles across the globe, academics interested in exercise research and those interested in sport-training research have worked rather independently (Pesce, 2012). Clearly, many sports involve high levels of energy expenditure during competition; however, much of players' training time is spent in practice drills that focus on specific actions that are precisely timed and executed. Researchers have attempted to determine whether learning sport skills alters fundamental cognitive processes and if sport experiences contribute to good decisions made off the playing fields. Sport skills learning may impact cognition, but conversely, selection processes in sport may favor those athletes who are more proficient in aspects of cognition relevant for sport performance. A meta-analytic review of cross-sectional studies by Voss and her colleagues (Voss, Kramer, Basak, Prakash, & Roberts, 2010) examined sports skills via a cognitive component skill approach, which evaluated the relation between the cognitive demands placed on athletes and their performance on laboratory tests of information processing speed, attention, and attentional regulation. Their review focused on sports that were characterized by the development of interceptive skills (e.g., tennis, fencing, and boxing) and sports that favored strategic skill (e.g., volleyball, basketball, soccer, hockey, field-hockey, and water polo). Overall, individuals who trained in sports evidenced better processing speed and attentional regulation when tested in a nonsport environment, suggesting that component processes may transfer from sport to other contexts. The analysis found no differences in cognitive test performance as a function of the type of sport, suggesting that the cognitive benefits derived from sport-skill training may not be sport specific. It will remain for controlled experimental research to support these conclusions, however.

The skill-acquisition perspective proposed in the present article suggests that virtually any complex movement activity, instructed properly, can improve an individual's cognitive function. Framed in question form: How do specific instructional contexts create conditions that alter peoples' psychological states and behaviors? It is plausible that instructional methods that optimize physical and mental challenge provide the conditions necessary to produce long-term changes in the way that individuals process information, make decisions, select movements, and experience the consequences of actions. If true, it would suggest that moderate-to-vigorous exercise is not a necessity for enhancing cognitive functions; rather, it is the skills involved in exercise being honed by instructional methods that impact cognition. If this explanation holds, exercise training may be only one of many types of movement activities that can enhance cognition. Support for this supposition is provided by an evaluation of research conducted on the development of the performing arts. Similar to people who excel in sports, individuals who are successful in the performance arts undergo years of extensive training and practice (Ericsson, 2014).

Performance Arts Instruction and Cognition

Not unlike advocates for routine exercise, supporters of the performing arts (e.g., instrumental music, dance, and theatrical acting) promote them as vehicles to improve children's and adolescents' mental development (Putkinen, Tervaniemi, Saarikivi, & Huotilainen, 2015; Schellenberg, 2005), to maintain cognitive capacities in older adults (Rogenmoser, Kernbach, Schlaug, & Gaser, 2018), and to support general mental health (Pratt, 2004). Despite similar predictions, theory-based research conducted to support the benefits of exercise and the arts on cognition has been conducted in relative isolation.

Of all the performing arts, the most studied activities are music and dance training. Similar to the construct of motricity, which is considered an evolutionary drive to move (Llinas, 2001), the construct of entrainment is considered as an evolutionary drive for movement synchronization such as the rhythm patterns seen in dance, foot tapping, and body sway and rocking (Salmelin & Hari, 1994). With respect to executive functions, the ability to synchronize one's movement with the movement of others when marching, dancing, or playing in a band depends on the ability to adjust movement timing on the basis of predicted and anticipated beat patterns (Mills, van der Steen, Schultz, & Keller, 2015; Pecenka & Keller, 2011). Similar to the construct of embodied enhancement of cognitive skills through motor skill acquisition described previously (Mavilidi et al., 2018; Moreau, 2015; Moreau et al., 2015), the construct of embodied music cognition has been a topic of interest to music researchers. Higher cognitive processing and emotional responses are thought to emerge as a function of the sensorimotor interplay between sensory input and motor output underlying music perception and production (Leman et al., 2013). To musicians, as is the case with athletes, it may be the "groove" of rhythmic actions that generates the pleasurable experiences that compel individuals to move and, in turn, help predict and interpret the proprioceptive inputs from their movements.

Data obtained from cross-sectional research and longitudinal studies suggest that music training has the potential to improve mental processes such as language acquisition and reading (Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014; Thomson & Goswami, 2008), verbal recall and reasoning skills (Forgeard, Winner, Norton, & Schlaug, 2008; Franklin, Moore, Yip, & Jonides, 2008), vocabulary skills (Schlaug, Norton, Overy, & Winner, 2005), and spatial skills (See reviews by Hetland, 2000; Vaughn, 2000). Neuropsychological studies also provide indirect support for relationships among music training, brain plasticity, and cognition (see reviews by Asbury & Rich, 2008; Schlaug, 2015; Wan & Schlaug, 2010). Reviewers propose that music training is a multisensory experience in which repetitive, timed motor actions are cued by auditory (metronome) and visual cues (musical notation) and are associated with multisensory feedback that strengthens connections between auditory and motor regions of the brain. The developing networks involved in the manipulation of symbolic information benefit processing of mental tasks outside of the music domain (Schlaug, 2015). Similar effects have been hypothesized to occur as a function of training in dance and other performance arts (Gazzaniga, 2008; Grafton & Cross, 2008; Posner, Rothbart, Sheese, & Kieras, 2008).

In summary, researchers are now beginning to explore how participation in sports and performance arts can enhance learner's cognitive functions. Wulf and Shea (2002) stressed that the instructional conditions in laboratory and naturalistic settings are quite different. Learning sports, music, dance, and other movement activities under real-world conditions may tap into many factors that are not addressed in the laboratory setting (e.g., personal relevance, goals, autonomy). Examining how skills are acquired in naturalistic settings over a long period of time with considerable physical and mental effort may provide additional insights into how instructional contexts alter metacognition (Roebers, 2017) and higher-level executive functions (Diamond, 2013). Few controlled studies have been conducted thus far, and data obtained from cross-sectional and longitudinal studies carried out under naturalistic conditions dominate the literature. While it is not possible to state definitive causal relations between sport or art experiences and cognition, advances have been made in identifying variables that impact skill acquisition and cognition via specific instructional methods. Unfortunately, as is the case with exercise studies, training interventions used in sports and arts studies are seldom described in sufficient detail to determine how instruction was provided and how skill progression was monitored. This methodological limitation serves as a recommendation for future research.

Presently, many exercise advocates recommend guidelines concerning the frequency and duration of moderate or vigorous activity needed to achieve physical and mental health benefits, including cognitive status (Physical Activity Guidelines Advisory Committee, 2018). Recall that recommendations for enhancing cognition are based primarily on neurocognitive research demonstrating the benefits of routine aerobic exercise on brain health (Hillman, Erickson, & Hatfield, 2017; Hillman et al., 2008). Given the skill-acquisition hypothesis proposed here, it may be the case that substantial cognitive benefits can be derived from training interventions that involve only moderate or even low levels of physical energy expenditure. Pesce and her colleagues (Pesce, Croce, et al., 2016) claimed that the intersection of chronic exercise and cognition and motor learning areas of research and praxis "has the potential to unwrap a new venue for sport sciences, inspiring novel research on complex motor learning in ecological physical activity and sport settings as a means for cognitive training" (p. 15). The present article broadens and deepens the focus intersecting multiple theoretical frameworks to highlight that both sports and the performing arts provide unique, naturalistic settings that shed light on the importance of skill acquisition on information processing, executive decision making, and strategy utilization. Sport and artistic proficiency benefits from the emergence of skills derived from years of training that emphasizes goal-related outcomes. As such, they provide an opportunity to assess the effects of the wide number of variables that moderate the relation between physical activity and cognition.

Conclusions

On the basis of a review of theory-based research exploring linkages between chronic exercise and cognitive function and a selective review of research that addressed associations between both sport and performance arts to cognitive function, several conclusions and recommendations are offered. These conclusions and recommendations resonate with those of other contemporary researchers whose ideas played pivotal roles in this article (e.g., Diamond & Ling, in press; Lewthwaite & Wulf, 2010; Moreau & Tomporowski, 2018).

The Process of Skill Acquisition Provides a Parsimonious Explanation for Observations Made Across Exercise, Sport, and Performing Art Studies

Researchers from different domains have examined relationships between movement activities and cognition. Despite similar theoretical interests, reviews of the literatures within these domains suggest that there is relatively little overlap or awareness of other literatures. Researchers have tended to focus on the merits of specific activities (e.g., types of exercises, music, or dance) to produce changes in cognitive functions, particularly executive functions. Despite the increased interest in the benefits of cross-disciplinary research over past decades, the academic "silo" effect continues to impede progress toward the development of unifying explanatory themes. Researchers across domains should strive to be part of broader frameworks that consider learners' abilities to integrate cognition, emotions, and behavior.

The Process of Skill Acquisition in Cognitive Training Programs is Understudied

Several reviewers suggest that mental engagement and attention to task are important instructional variables to consider, but few describe closely the characteristics of interventions designed to capture these psychological processes. Creating an optimal training zone may require the application of methods developed by educational specialists who are trained to determine when and how to vary intervention methods that elicit mental engagement. Reliable indices of instructional fidelity will be essential to determine the impact of skill-acquisition training on cognition. Observational time-sampling techniques have been developed to assess teacher-student interactions during physical activity programs; however, standardized methods that assess learner engagement are lacking.

The Allocation of Mental Resources Required During Skill Acquisition, Independently From or Interactively With the Level of Physical Energy Expenditure, Is Essential for Reaping the Largest Cognitive Benefits

Moderate-to vigorous exercise may be important to derive physical fitness, but it may not be essential for cognitive benefits. Learning to play a new musical piece or instrument or execute a new dance step or basketball move typically involves substantial practice performed with relatively low levels of physical exertion. An individual's level of physical fitness may play a role in maintaining practice, rate of improvement, and level of proficiency, but it does not serve as a mediator. However, fitness may serve as a moderator: a threshold fitness level may be necessary for an optimal exploitation of the mechanism mediating cognitive engagement effects on cognition. The adaptations in neurological structures observed with arts training suggest that exercise training is not a unique intervention. This review acknowledges the lack of emphasis on neurocognitive research as a limitation; hopefully, this important body of evidence can be addressed in the future.

Outcome Measures Other Than Executive Functions Are Understudied

Presently, studies that focus either on exercise or the performance arts typically concentrate on a relatively restricted number of outcome measures; most often tests measure components of executive functions (e.g., task switching, response inhibition, and updating). The inclusion of other cognitive variables (e.g., metacognition, long-term memory, higher executive functions, and problem solving), and psycho-social variables (e.g., self-efficacy, autonomy, self-appraisal, and personality) may provide convergent evidence for the relation between skill-training and cognition.

Cognitive Benefits Obtained Via Skill-Acquisition Interventions Are Enduring

Motor skill acquisition leads to procedural learning, which can be retained for long periods of time. The adage that "you never forget how to ride a bicycle" holds true for skills that are obtained with extensive practice. Motor programs are thought to be encoded into long-term memory and are available when needed. Although disuse of skeletal muscle may lead to reduced contractile capacity and weakness, the neuro-excitatory couplings and patterns of activation that were created remain. This conclusion differs from that of exercise researchers who propose a "use-it-or-lose-it" hypothesis, which predicts that gains in executive functions derived from physical activity will wane with physical inactivity and that continued exercise is required to maintain optimal mental functioning.

Naturalistic Translational Research Studies Complement Controlled Experiments

Motor learning has been studied extensively in experiments performed under laboratory conditions. Consider, however, that the skills learned in many sports, movement arts, and occupations require years of practice, during which participants perform a massive number of physical practice trials. The considerable drive and willingness to expend physical and mental resources that are demanded in naturalistic settings are difficult to capture in controlled laboratory settings. There are numerous physical activities that researchers can study in naturalistic contexts that provide insights into the cognitive processes that are central to the development of learned motor programs. Besides the huge number of children, adolescents, and adults who enroll in sport or exercise programs, equal numbers of others are drawn to dance, music, theater, and video-games. All provide unique opportunities to gather information concerning physical activity and skill advancement, and their impact on cognitive processes and transfer across multiple tasks and situations.

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