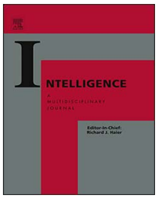
Intelligence 66 (2018) 32–43

Contents lists available at ScienceDirect

Intelligence

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



Multi-modal fitness and cognitive training to enhance fluid intelligence

Ana M. Daugherty[a,g,*], Christopher Zwilling[a,g], Erick J. Paul[a,g], Nikolai Sherepa[a,g], Courtney Allen[a,g], Arthur F. Kramer[b,c,d], Charles H. Hillman[c], Neal J. Cohen[a,e], Aron K. Barbey[a,f,g,h,i,*]

[a] *Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, 405 N Matthews Ave, Urbana, IL 61801, United States*
[b] *Office of the Provost, Northeastern University; 100 CH, 360 Huntington Ave, Boston, MA 02115, United States*
[c] *Department of Psychology, Northeastern University; 125 Nightingale Hall, 360 Huntington Ave, Boston, MA 02115, United States*
[d] *Department of Mechanical & Industrial Engineering, Northeastern University, 360 Huntington Ave, Boston, MA 02115, United States*
[e] *Center for Nutrition, Learning, and Memory, University of Illinois at Urbana-Champaign, IL 61801, United States*
[f] *Department of Psychology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States*
[g] *Decision Neuroscience Laboratory, University of Illinois at Urbana-Champaign, IL, United States*
[h] *Department of Bioengineering, University of Illinois at Urbana-Champaign, IL, United States*
[i] *Neuroscience Program, University of Illinois at Urbana-Champaign, IL, United States*

ARTICLE INFO

Keywords:
Reasoning
Mindfulness
Fitness
Latent modeling

ABSTRACT

Improving fluid intelligence is an enduring research aim in the psychological and brain sciences that has motivated public interest and scientific scrutiny. At issue is the efficacy of prominent interventions—including fitness training, computer-based cognitive training, and mindfulness meditation—to improve performance on untrained tests of intellectual ability. To investigate this issue, we conducted a comprehensive 4-month randomized controlled trial in which 424 healthy adults (age 18–43 years) were enrolled in one of four conditions: (1) Fitness training; (2) Fitness training and computer-based cognitive training; (3) Fitness, cognitive training, and mindfulness meditation; or (4) Active control. Intervention effects were evaluated within a structural equation modeling framework that included repeated-testing gains, as well as novel tests of fluid intelligence that were administered only at post-intervention. The combination of fitness and cognitive training produced gains in visuospatial reasoning that were greater than in the Active Control, but not in performance on novel tests administered only at post-intervention. Individuals more variably responded to multi-modal training that additionally incorporated mindfulness meditation (and less time spent on cognitive training), and those who demonstrated repeated-testing gains in visuospatial reasoning also performed better on novel tests of fluid intelligence at post-intervention. In contrast to the multi-modal interventions, fitness only training did not produce Active Control-adjusted gains in task performance. Because fluid intelligence test scores predict real-world outcomes across the lifespan, boosting intelligence ability via multi-modal intervention that is effective even in young, healthy adults is a promising avenue to improve reasoning and decision making in daily life.

1. Introduction

An enduring research aim in the psychological and brain sciences is to enhance brain health and to deliver sustainable cognitive gains that benefit daily living. A central question in this effort is whether experimental interventions can enhance general intelligence. General intelligence captures the statistical regularities in performance across a wide range of cognitive domains, including reasoning, problem solving, and decision making (Barbey, 2017; Spearman, 1927). Within this framework, fluid intelligence (G_f) that encompasses pattern detection and problem solving is distinguishable from static knowledge and skills in crystallized intelligence (Carroll, 1993; Cattell, 1963). Higher intelligence scores predict real-world outcomes across the lifespan: better scholastic achievement (Gottfredson, 1997; Kuncel & Hezlett, 2007), job performance (Hunter, 1986; Salgado et al., 2003), and career success (Hagmann-von Arx, Gygi, Weidmann, & Grob, 2016). Although it can be conceived as a stable trait (Carroll, 1993; Jensen, 1998), the prospect of enhancing intelligence—thereby improving reasoning and decision making in daily life—remains intriguing. This pursuit has renewed vigor following recent reports of training gains in G_f (e.g.,

---

[*] Corresponding authors at: Decision Neuroscience Laboratory, Beckman Institute for Advanced Science and Technology, 405 N Matthews Ave, Urbana, IL 61801, United States. URL: https://www.DecisionNeuroscienceLab.org

E-mail addresses: adaugher@illinois.edu (A.M. Daugherty), barbey@illinois.edu (A.K. Barbey).

https://doi.org/10.1016/j.intell.2017.11.001
Received 11 April 2017; Received in revised form 22 October 2017; Accepted 6 November 2017

Jaeggi, Buschkuehl, Jonides, & Perrig, 2008), yet it has been met with mixed results and inconsistent replication (e.g., Chooi & Thompson, 2012; Harrison et al., 2013; Jaeggi et al., 2010; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Redick et al., 2013; Thompson et al., 2013). Discrepant evidence may in part be due to differences in intervention methods and an incomplete theoretical model of the relevant mechanisms (see Greenwood & Parasuraman, 2015 for a review).

Aerobic exercise that delivers global effects to brain health has long been a focus for interventions aimed to promote cognitive function. The brain carries hefty metabolic demands that are serviced by its large vascular endothelial network (Attwell & Laughlin, 2001). The link between vascular health, brain integrity and cognitive function is well documented (Hillman, Erickson, & Kramer, 2008; Raz & Rodrigue, 2006; Warsch & Wright, 2010). Physical activity that promotes endothelial function is associated with better cognitive outcomes (Colcombe & Kramer, 2003; Smith et al., 2010), including G_f (Talukdar et al., 2017; Elsayed, Ismail, & Young, 1980; Reed, Einstein, Hahn, Gross, & Kravitz, 2010), working memory (Pontifex et al., 2014; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009), and executive functions (Scott, Souza, Koehler, Petkus, & Murray-Kolb, 2016). Poor cardiovascular health and chronic neuroinflammation are associated with worse G_f (Spryidaki et al., 2014), and frequent exercise reduces these risk factors and promotes G_f ability across the lifespan (Karr, Areshenkoff, Rast, & Garcia-Barrera, 2014; Reed et al., 2010; Singh-Manoux, Hillsdon, Brunner, & Marmot, 2005). The magnitude of gains is dependent upon the level of activity and duration of intervention (Colcombe & Kramer, 2003; Karr et al., 2014; Smith et al., 2010), but even moderate-level aerobic activity over several weeks has demonstrated benefits. These cognitive effects are plausibly conferred by microstructural changes throughout the brain, including synaptogenesis, neurogenesis, increased production of nerve growth factors and other important cellular and molecular changes (Schwarb et al., 2017; Erickson, Hillman, & Kramer, 2015; Gomez-Pinilla & Hillman, 2013; Voss, Vivar, Kramer, & van Praag, 2013), and changes in functional activation (Kleemeyer et al., 2017). Exercise-related microstructural changes in the brain are considered to be dynamic and to persist beyond prescribed intervention duration to produce potentially long-term effects (Colcombe & Kramer, 2003; Gomez-Pinilla & Hillman, 2013); although frequent, habitual activity is expected to produce more sustainable change (Erickson et al., 2015). In this manner, global benefits of cardiorespiratory fitness to brain function, even following a relatively short intervention period, may encourage better response to other cognitive-based interventions aimed to bolster intelligence.

Cognitive interventions to promote higher G_f commonly target working memory abilities that appear closely related to performance on intelligence tests (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Barbey, Colom, Paul, & Grafman, 2014; Barbey et al., 2012; also see Martinez et al., 2011). Working memory capacity is central to other cognitive abilities (Barbey, Koenigs, & Grafman, 2013; Engle et al., 1999; Oberauer, Schulze, Wilhelm, & Süss, 2005), especially when performing complex mental operations with demands on attention and inhibition (Harrison et al., 2013). Thus, interventions aimed to improve working memory capacity may buttress general cognitive ability. Several studies have reported the transfer of working memory task gains to general cognition (e.g., Jaeggi et al., 2008; Jaeggi et al., 2010; Klingberg et al., 2005; Klingberg, Fonsberg, & Westerberg, 2002; Dahlin, Nyberg, Bäckman, & Neely, 2008; Baniqued et al., 2013; but also see Harrison et al., 2013). However, effect sizes are highly variable (see Melby-Lervåg & Hulme, 2013; Danielsson, Zottarel, Palmqvist, & Lanfranchi, 2015; Melby-Lervåg, Redick, & Hulme, 2016 for meta-analyses), producing contradictory views of cognitive training regimens that motivate further research and debate (Shipstead, Redick, & Engle, 2012, Buschkuehl & Jaeggi, 2010; Morrison & Chein, 2011; Schwaighofer, Fischer, & Buhner, 2015; Dougherty, Hamovitz, & Tidwell, 2016; van Heugten, Ponds, & Kessels, 2016 for reviews). Working memory relies on several neural correlates, including the striatum and prefrontal cortex (Barbey et al., 2013), that are sensitive to changes in cardiorespiratory fitness (Diamond, 2013). Therefore, aerobic activity that bolsters function of relevant neural substrates may facilitate cognitive training and its transfer to fluid intelligence.

An alternative to directly training working memory ability is to indirectly promote it and its contribution to G_f with interventions that target other aspects of cognitive performance (Ward et al., 2017). For example, training in mindfulness—the ability to monitor one's thoughts and limit mind wandering—may minimize the impact of distraction during test taking to indirectly improve indices of cognitive ability. Mind wandering is negatively correlated with scores on tests of working memory, G_f, and scholastic aptitude (Mrazek et al., 2012), and mindfulness training appears to prevent this to improve test scores (Banks, Welhaf, & Srour, 2015; Brown et al., 2011; Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Noone, Bunting, & Hogan, 2016). Training in mindfulness technique improves self-referential thought that fosters better executive functioning, including attentional control (Tang, Holzel, & Posner, 2015), which is also a putative mechanism of cognitive training effects on G_f (Greenwood & Parasuraman, 2015). Thus, better task attention via mindfulness may improve cognitive training and boost performance on tests of G_f. Moreover, the combination of aerobic exercise, mindfulness meditation and cognitive training, that each promotes executive functions, may produce additive gains that surpass exercise alone. Each of these intervention strategies has been considered before, and here we test multi-modal interventions that may optimally engage the neural and cognitive constituents of fluid intelligence.

Fundamental to determining the relevant mechanism to promote G_f function is the assessment of intervention efficacy via testing gains. Foremost, the study of "gain" requires a longitudinal, pre-post test design and appropriate statistical tests of change (McArdle, 2009). Repeated-testing gains, or "practice effects", confound the interpretation of interventions aimed at improving cognition, and thus comparison to a randomized control group is a second consideration. However, repeated-testing gains theoretically reflect the function of intact cognitive systems for which the tests are designed to measure (Thorvaldsson, Hofer, Hassing, & Johansson, 2005) and characterizing individual differences in the magnitude (and direction) of change is a means to evaluate these functions that scaffold intelligence (e.g., Baltes, Dittmann-Kohli, & Kliegel, 1986; Hertzog & Schaie, 1986, 1988; Hertzog, von Oertzen, Ghisletta, & Lindenbrger, 2008; McArdle, 2009). Additional measures of fluid intelligence ability were administered only at post-intervention to avoid the contribution of practice effects and therefore to provide further insight into individual differences in response to interventions. When accounting for pre-intervention cognitive ability, higher scores in intervention groups as compared to control on the novel tasks of G_f taken at post-intervention may indicate a boost to intelligence. In the absence of such effects, greater repeated-testing gains that are associated with higher post-intervention G_f scores on novel tests may indicate the transfer of components relevant to task performance other than general intelligence—e.g., attention, motivation, and strategy (Hayes, Petrov, & Sederberg, 2015).

We investigate the efficacy of multi-modal interventions to enhance G_f within a four-month randomized control trial of young adults assigned to either an active control, or an experimental condition— fitness (Fit); fitness and cognitive training with a suite of adaptive computer games, Mind Frontiers (Fit-MF); fitness, cognitive training, and mindfulness training (Fit-MF-Mind). G_f was assessed in two ways: repeated-testing pre- and post-intervention with parallel forms of a canonical fluid intelligence test (Figure Series) and an achievement test of analogical reasoning (Law School Admission Test; LSAT), as well as a collection of fluid intelligence indices that were assessed only at post-intervention. Within a latent modeling framework (McArdle, 2009) we test three hypotheses (1) As compared to Active Control, interventions will account for better post-intervention G_f assessed by novel tests (defined by letter series, number series, matrix reasoning, and Shipley