

8-1-2013

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Lori A. Sherlock

West Virginia University, lsherlock@hsc.wvu.edu

W. Guyton Hornsby, Jr.

West Virginia University

James Rye

West Virginia University

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Recommended Citation

Sherlock, Lori A.; Hornsby, Jr., W. Guyton; and Rye, James (2013) "Physiological Effects of Aquatic Exercise on Cognitive Function in the Aging Population," *International Journal of Aquatic Research and Education*: Vol. 7 : No. 3 , Article 9.

DOI: 10.25035/ijare.07.03.09

Available at: <https://scholarworks.bgsu.edu/ijare/vol7/iss3/9>

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The Physiological Effects of Aquatic Exercise on Cognitive Function in the Aging Population

Lori A. Sherlock, W. Guyton Hornsby, Jr., and James Rye

Neurocognitive decline, including Alzheimer's disease and other forms of dementia, is considered to be the world's fastest growing disease (Alzheimer's Association, 2011). Due to this escalation, research focused on determining causes, accelerants, impeding factors, and preventative strategies has become a focus of interest within the field. One of the principal points of study is the role that exercise plays in the maintenance or fortification against neurocognitive decline. Though there is a robust library of research focused on the effects of land-based exercise on cognitive function, currently there is no research that discusses the impact of aquatic-based exercise on these parameters. This paper will examine the effects of land-based exercise on cognitive function while bridging these results to the aquatic environment.

The aging process is comprised of many regular changes that occur in a maturing population across a lifespan. Both physical and cognitive decrements have been noted with increasing age resulting in accumulative concern for quality of life, medical costs, and loss of independence. Connections to increasing age have been linked to cognitive decline after peaking during early adulthood (Hillman et al., 2009; Park & Reuter-Lorenz, 2009), and symptoms have been noted to begin rapidly accelerating after age 60 (Barnes et al., 2007). Adults age 85 and older are reported to have a rate of dementia of nearly 50% (Park & Reuter-Lorenz, 2009). This neurocognitive frailty is a serious concern for the aging population; it affects an individual's ability to age efficaciously and may be one of the largest threats to successful aging in our society (Park & Reuter-Lorenz, 2009).

Research on neurocognitive frailty associated with the aging process has focused on exercise as a means of maintaining or fortifying cognitive ability and executive function. Both acute and chronic physical activity have been linked to significant cognitive, as well as physical benefit (Denkinger, Nikolaus, Denkinger, & Lukas, 2012; Middleton, Barnes, Lui, & Yaffe, 2010). Though the current research body has distinguished this link utilizing primarily land-based exercise interventions, the aquatic environment may provide added stimulus to further enhance executive function via physiological mechanisms and environmental enrichment.

Lori Sherlock and W. Guyton Hornsby are with the Department of Exercise Physiology, and James Rye is with the Curriculum and Instruction/Literacy Studies Department, all at West Virginia University in Morgantown, WV.

Age-Related Changes in Brain Structure

Structural decline within the frontal, parietal, and temporal lobes of the brain resulting in decrements in cognitive processes begin after early adulthood (after age 30) according to some research (Raz & Rodrigue, 2006; Park & Reuter-Lorenz, 2009). Total brain volume is reduced by approximately 5% per decade after age 40 with the greatest size reduction being observed in the caudate, cerebellum, hippocampus, and prefrontal areas (Park & Reuter-Lorenz, 2009; Scahill et al., 2003). There has also been evidence for declining volume of gray and white matter in the older adult with particular decrements being noted in the frontal and parietal cortex occurring after the fifth decade of life (Park & Reuter-Lorenz, 2009; Raz & Rodrigue, 2006). Dopaminergic receptors and synaptic density have similarly been shown to be reduced in quantity with age (Park & Reuter-Lorenz, 2009) while neuronal shrinkage and dysmorphology, dendritic spine loss, and neuronal body loss have similarly been noted with the aging process (Myers, 2008). Due to these structural neuronal alterations, information processing becomes less efficient. Processing speed, working memory capacity, and attention can all be adversely affected (Park & Reuter-Lorenz, 2009). Other components of memory remain virtually untouched by the aging process including long-term memory and implicit memory (Park & Reuter-Lorenz, 2009).

Exercise and Brain Structures

Aerobic Exercise

Aerobic training has been noted to have both acute and chronic effects on various components of executive function (Liu-Ambrose et al., 2010; Baker et al., 2010; Barnes, Yaffe, Satariano, & Tager, 2003; Bielak, 2010; Budde, Voelcker-Rehage, Pietrabyk-Kendziorra, Ribeiro, & Tidow, 2008; Davis et al., 2007; Davis et al., 2007; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Liu-Ambrose et al., 2008; Swardfager et al., 2010; Teixeira et al., 2012). Research supports the link between participation in chronic aerobic exercise and improvements in spatial learning, memory, cognitive capacity, selective and divided attention, working memory, cognitive flexibility, planning, inhibition, decision making, problem solving, cognitive speed, and overall cognitive function (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008; Baker et al., 2010; Barnes et al., 2003; Birren & Fisher, 1995; Budde et al., 2008; Fabre, Chamari, Mucci, Masse-Biron, & Prefaut, 2002; Hillman et al., 2009; Hillman, Erickson, & Kramer, 2008; Hillman, Snook, & Jerome, 2003; Ke, Huang, Liang, & Hsieh-Li, 2011; Liu-Ambrose et al., 2010; Man, Tsang, & Hui-Chan, 2010; Scherder, Eggermont, Geuze, Vis, & Verkerke, 2010; Smith et al., 2010; Van der Borght, Havekes, Bos, Eggen, & Van der Zee, 2007; Teixeira et al., 2012; Yáñez, Shaw, Morris, & Matthews, 2011). Aerobic training has also been correlated with increased cerebral electrical activity and neurotransmitter secretion as well as reductions in neural apoptosis, increased growth factor modulation, increased vascularization, declines in brain volume loss, and decelerated memory loss (Asl, Sheikzade, Torchi, Roshangar, & Khamnei, 2008; Baker et al., 2010; Berkman et al., 1993; Blumenthal & Madden, 1988; Burns et al., 2008; Chaddock et al., 2010; Chan et al., 2005; Clarkson-Smith & Hartley, 1989; Deeny et al., 2008;

Erickson et al., 2011; Erickson et al., 2009; Fabre et al., 2002; Flöel et al., 2010; Goekint et al., 2010; Hillman et al., 2009; Hillman et al., 2008; Ke et al., 2011; Kim et al., 2010; Klusmann et al., 2010; Komulainen et al., 2010; Komulainen et al., 2008; McAuley et al., 2011; Nation et al., 2011).

The effects of a single acute bout of aerobic exercise have also been studied. Findings support neuropsychological improvements including increased attention, processing speed, concentration, and overall cognitive function (Budde et al., 2008; Carles et al., 2007; Coles & Tomporowski, 2008; Goekint et al., 2010; Hillman et al., 2009; Hillman et al., 2008; Hillman et al., 2003; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009).

The acute and chronic effects of aerobic training are widely documented and provide some insight linking the effects of exercise with executive function. The overall outcome of exercise is enhanced immune condition of the brain and its structures that results in improved neural plasticity. Though the majority of the studies that have been performed exhibit positive results associated with participation in exercise or accrual of cardiovascular fitness, there are some studies that do not display any variations in executive function with the addition of physical activity. These studies may not provide supporting evidence that aerobic training results in positive modifications in cognitive processes; however, they likewise do not illustrate any decrements.

Anaerobic Exercise

Anaerobic exercise in the form of strength training or short, intense bouts of exercise has not been a primary focus of study in relation to executive function. There are a limited number of studies that have addressed the use of this modality for cognitive adaptations. The chronic anaerobic training literature has reported no significant effects on neurocognitive function with varied levels of intensity (Liu-Ambrose et al., 2010; Pontifex et al., 2009). Acute effects of anaerobic training (effects noted during or immediately following the training stimulus) have reported increased levels of brain-derived neurotrophic factor (BDNF), epinephrine, and norepinephrine. Acute effects also include increased speed and improved reaction time, as well as working memory span, response inhibition, improved recall, accuracy, and learning efficiency (Lachman, Neupert, Bertrand, and Jette, 2006; Liu-Ambrose et al., 2010; Pontifex et al., 2009).

Combined Training

According to a meta-analytic study conducted by Colcombe and Kramer (2003, p. 128), “participants in combined strength and aerobic training regimens improved to a reliably greater degree than those in aerobic training alone.” This finding may be due to the physiological variations in stimuli resulting in a more diverse manifestation of cognitive improvements (Colcombe & Kramer, 2003). Improvement in fitness parameters including strength, range of motion, and VO_{2max} can be achieved with both resistance training as well as aerobic training (Farrell, 2011; Komulainen et al., 2010). Additionally, fitness improvement may be more achievable if individuals participate in multimodal forms of exercise such as resistance training with aerobic training, or sprinting with moderate aerobic training.

Exercise Intensity and Duration

Exercise intensity, the extent of the physiological disruption or stress of the physical activity being performed, is multifactorial and may play a role in altering executive function. Age, training status, gender, environmental conditions, and health status all affect both the perception of exercise intensity and actual, absolute exercise intensity as measured by energy expenditure or VO_2 . Implications that specifications or personalization in intensity of exercise, or total energy expenditure may result in increased benefits for cognitive function have been suggested (Angevaren, Vanhees, Nooyens, Wendel-Vos, & Verschuren, 2010; Fabre et al., 2002; Flöel et al., 2010; Middleton et al., 2011). Overall, recommendations for moderate to intense exercise have been well supported for improvements in executive function (Erickson et al., 2011; Radák et al., 2010; Stroth, Hille, Spitzer, & Reinhardt, 2009; van Uffelen, Chinapaw, Hopman-Rock, & van Mechelen, 2009; Zlomanczuk et al., 2006).

Duration of exercise training, or the time spent participating in the exercise bout, is considered to be another integral factor in determining effectiveness of an exercise intervention on cognitive function. Some studies report findings to support that duration provided the greatest impact on cognitive function (Davis et al., 2008). A review of literature conducted by Denking et al. (2012) indicated that the gold standard for cognitive intervention via exercise is 30 min of physical activity performed 5 times per week. This standard corresponds to the recommendations issued by the American College of Sports Medicine (ACSM) for general cardiorespiratory health and wellness.

Exercise Environment

The environment in which an individual is immersed can play a major role in the maintenance and development of executive function (Bielak, 2010; Zec, 1995). An environment that provides participants a means of stimuli, known as an 'enriched environment,' positively influences neurologic processes to become more efficient (Bielak, 2010; Hultsch, Hertzog, Small, & Dixon, 1999; Zec, 1995). This stimulus could be obtained from exercise, cognitively challenging activities, or a complex environment. A complex environment can be described as an individual's exposure to changing contextual variables or diverse stimuli that require the individual to make multiple, complex decisions that place demand on their cognitive skills. Adaptivity and plasticity of neural structures via cerebral blood flow, increasing numbers of neural synapses or synaptic organization, hippocampal neurogenesis, neuronal survival, or an upsurge in neurochemical availability are all possible physiological explanations for this phenomenon (Bielak, 2010; Blackmore, Golmohammadi, Large, Waters, & Rietze, 2009; Galvan & Jin, 2007; Galvan & Bredesen, 2007; Hillman et al., 2008). These adaptations are theorized to occur within an enriched environment due to the fluctuating environmental needs resulting in the necessity for the central nervous system to recognize and perceive varying sensory input then determine and create an appropriate motor response corresponding with proper sequencing, timing, and coordination necessary for the action (Binder, Storandt, & Birge, 1999; Hultsch et al., 1999). The key component essential for the complex environment to deliver is a necessity for engagement in cognitively demanding situations (Hultsch et al., 1999).

Potential Effects of the Aquatic Environment on Cognitive Function

The aquatic environment boasts of being one of the most malleable exercise environments available and can provide a variety of benefits to a range of populations. The physical properties of water modify many physiological aspects of human function and thus have a direct reaction on exercise physiology.

Density and Specific Gravity

In an aquatic setting, density of an individual's body in relation to the water's density (otherwise known as specific gravity) is very important for maintenance of body position as well as dynamic balance. Thus, density and specific gravity can provide new challenges to individuals exercising in the water. Because of individualistic nature of density, specific gravity, and body fat distribution, each person entering the water is confronted uniquely with modifying muscular contractions, somatic awareness and concentration to maintain appropriate exercising posture. This can be made easier for some by increasing grounding forces (the effect of gravity) via adding weights to an individual's ankles or allowing time for adjustment by working in more shallow water where gravity remains the dominating force over buoyancy. Consequently, the effects can be gradually progressed to allow for greater stimulus from the aquatic environment. This can add another dimension to exercise intended to promote executive function. As noted previously, adding coordination, concentration or other cognitively demanding variables to exercise can result in more positive outcomes on cognitive performance (Bielak, 2010; Binder et al., 1999; Blackmore et al., 2009; Galvan & Jin, 2007; Galvan & Bredesen, 2007; Hillman et al., 2008; Small et al., 2006; Stroth et al., 2009; Zec, 1995).

Buoyancy

As an individual enters the water and becomes immersed, water is displaced and a buoyant effect is experienced that counteracts the gravitational force. This feature of the aquatic environment provides an option for 'weightless' exercise and can offer assistance, resistance, or support. These attributes associated with buoyancy can allow for greater comfort and involvement when participating in exercise or be used to challenge the immersed body. Buoyancy, in relation to density and specific gravity, also can offset the body's equilibrium when immersed to provide a challenge for postural maintenance and locomotor control. The additional perturbation can increase the cognitive demands during the exercise intervention to provide for greater cognitive stimuli resulting in improvements in executive function.

Hydrostatic Pressure

Hydrostatic pressure is the pressure exerted upon a body immersed in water. The applied pressure provides support to the physiological systems by assisting blood return to the heart and lymphatic fluid redistribution throughout the body (Gulick, 2010; Mourot et al., 2010). The effect of hydrostatic pressure enhancing venous return to the heart is a major contributing factor to a net reduction in heart rate

while immersed (Becker & Cole, 2011; Krueger et al., 2009). Veins and venous blood flow are highly affected by external pressure, including muscular compression and hydrostatic pressure; thus, immersion results in a net increase in central venous pressure leading to a greater return of blood to the heart that shifts the heart rate downward. The result of this blood shift is an increase in central volume, cardiac volume, mean stroke volume, and cardiac output leading to a more efficient cardiovascular system. Another result of the increased blood distribution is an increase in circulatory capacity, or greater availability of blood to shunt to the working tissues. Though circulatory impact of immersion has not been studied in the brain, it is accepted that muscular blood flow more than doubles with immersion (1.8 ml/min/100 g of tissue on land to 4.1 ml/min/100 g of tissue in neck-depth water) as does the metabolic waste removal capability of the circulatory system (increases seen were 225% above that of land metabolic waste removal; Balldin, Dahlback, & Lundgren, 1971). Hydrostatic pressure also supplies enough pressure around the thoracic cavity, via direct pressure and reallocation of blood into the chest cavity, to increase the work of respiration by 60% (Hong, Cerretelli, Cruz, & Rahn, 1969). In addition, hydrostatic pressure is theorized to provide a stimulation overload via skin sensory nerve endings including temperature, touch, and pressure receptors throughout the body to elicit a reduction in pain sensation (Günther, Mur, Kinigadner, & Miller, 1994).

All of these varying stimuli produce an aquatic environment that provides the body with novel stimuli that may further engage the cognitive processes to reduce cognitive dysfunction. Enhanced circulation may also prove to further augment cognitive maintenance or development. As stated previously, the literature supports that improvement in cerebral blood flow may produce positive structural modifications in cerebral tissue that promote improved executive function (Barnes et al., 2003; Bielak, 2010; Deeny et al., 2008; Lachman, et al., 2006; Man et al., 2010; Scherder et al., 2010; Small et al., 2006).

Viscosity

The viscosity, or relative thickness of a liquid, delivers a much higher resistance than that of air resulting in an increased amount of force required to elicit movement. Viscosity of water does not become a relative variable until movement is produced by a body or limb. The force needed to move a body, limb, or object through the water is highly related to the speed of movement being produced, the frontal surface area and shape of the object being moved through the water, and the amount of turbulent flow present in the water during the movement.

Due to the variability of contractile forces, muscular recruitment, and stimuli, neuromuscular recruitment patterns are altered highly in an aquatic setting (Colado, Triplett, Tella, Saucedo, & Abellan, 2009a; Colado, Tella, Triplett, & Gonzalez, 2009b; Colado, Tella, & Triplett, 2008; Triplett et al., 2009c). Theoretically, this could yield adaptation to cerebral function, hormonal interactions, or even neurogenesis by adding new, complex movement patterns into an individual's exercise prescription to develop a more enriched environment (Budde et al., 2008; Hulstsch et al., 1999; Klusmann et al., 2010; Man et al., 2010; Stroth et al., 2009). It has also been noted that combined exercise training (resistance training paired with aerobic training) may improve to a greater degree than just using a single modality

(Colcombe & Kramer, 2003). The aquatic environment lends itself well to applying this theory as every movement produced is counteracted by the viscous force of water thus promoting resistance training while performing aerobic training.

Conclusions on the Aquatic Environment

Generally speaking, the greater the level of immersion, the greater the effect the aquatic environment will elicit on the immersed body. Many physiological effects are produced during immersion that could potentially affect executive function. The environment in and of itself affords various new stimuli to further develop the exercise session from mere exercise to exercise within a more enriched environment. The challenges that the physical attributes of the aquatic environment lend to individuals in the pool also drive the requirement for added concentration, variance of muscular contractions, and coordination while performing aquatic exercise. The buoyant support that the water provides may increase comfort during exercise for a variety of populations allowing them to enjoy the exercise experience more while promoting participation that can lead to longevity. Lastly, the increase in circulatory function that augments blood availability may potentially lead to increased cerebral circulation which has been definitively seen to promote neural structure maintenance and growth (Barnes et al., 2003; Bielak, 2010; Deeny et al., 2008; Lachman, et al., 2006; Man et al., 2010; Scherder et al., 2010; Small et al., 2006).

All of these aspects of participating in water exercise have the potential to promote, enhance, or even improve upon the effects of dry-land exercise on cognitive function. It is well accepted that land exercise promotes a multifaceted chain of reactions to stimulate positive alterations in executive function but these progressive results could be augmented by modifying the exercise medium. With the addition of immersing the body while performing exercise, the individual could potentially experience a heightened level of executive function adaptation prompted by greater environmental stimulation and improved circulation. In addition, adherence and continuation of exercise participation may also be superior. Studies support a higher level of both adherence and exercise continuation when the physical activity is performed in water (Bennell & Hinman, 2011; Munguía-Izquierdo & Legaz-Arrese, 2008; Kang, Ferrans, Kim, Kim, & Lee, 2007; Wang, Belza, Elaine, Whitney, & Bennett, 2007; Belza, Topolski, Kinne, Patrick, & Ramsey, 2002). This may be, in part, due to the sensation of security that the water provides, the reduction in pain stimulated by hydrostatic pressure, or the off-loading of the joints promoted by the upward force of buoyancy. Regardless of the reasons behind this finding, continuation of exercise is noted to be paramount for continued cognitive benefits (Barnes et al., 2007; Erickson et al., 2009; Weuve et al., 2004). Thus the water may be the ideal medium for promoting neural benefits and executive function for this sole reason.

Conclusions

The aging process has vast effects on executive function that result in diminished quality of life, increased medical costs, and loss of independence. Age-related changes in brain structure primarily occurring within the frontal, parietal, and temporal lobes beginning after the age of 30 have been distinguished as one of the

primary causes related to age-related cognitive decline (Raz & Rodrigue, 2006; Park & Reuter-Lorenz, 2009). Fortunately, these neurophysiological alterations can be curtailed or even overturned with the inclusion of physical activity and accrual of fitness.

Exercise can acutely or chronically affect the somatic systems to provide alterations resulting in improvements in cognitive function. The varying physical properties of water may provide further opportunity for cognitive adaptation via utilizing both the physiological attributes (somatic stimulation and enhanced circulation) as well as the environmental qualities (support, resistance, and comfort) that the aquatic environment possess. Aquatic exercise may be the ideal mode and medium to enhance cognitive function in the aging population. Further research is needed to support or refute this hypothesis.

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