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Neuropsychological, Cognitive and Physiological Implications of Barefoot Running on Working Memory

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Abstract

The aim of the present study was to compare the effects of barefoot versus shod running on working memory. I recruited exercise science students from the University of North Florida who exercised recreationally. Participants ran both barefoot and shod while hitting targets (poker chips) on a running track and without targets. I measured working memory using backward digit recall and also recorded participants' heart rate, speed, and target accuracy. The main finding from this study was that working memory performance increased in the barefoot condition when participants hit targets (poker chips). This result supports the idea that additional attention is needed when running barefoot to avoid stepping on objects that could potentially cause harm to the foot. Significant increases in participant's heart rate were also found in the barefoot condition but not in the shod condition. No significant differences found in participants' speed in the barefoot or shod condition, nor were there any in the target or no target condition. Together, these findings suggest that individuals working memory increases after at least sixteen minutes of barefoot running if they have to look at the ground to avoid objects that may cause harm to their feet. Barefoot running may help individuals of all ages; from delaying the onset of cognitive deterioration in the elderly, obesity prevention for individuals of all ages, to providing a boost in cognitive performance for children who are behind their peers in school.

Keywords: attention, barefoot, heart rate, running, speed, working memory

The Effect of Barefoot Running on Working Memory

I. Aerobic Exercise has Physical Benefits

It has been long established that aerobic exercise has many health benefits including a lower risk of developing hypertension, diabetes, and coronary heart disease (Boule, Haddad, Kenny, Wells & Sigal, 2001; Williams & Thompson, 2013). Aerobic exercise also increases coronary blood flow and cerebral blood flow (Duncker & Bache, 2008; Querido & Sheel, 2007). Regulation of blood flow during exercise is not only important for new cell growth but it serves as a preventative tool in cerebrovascular and neurological diseases (Gustafsson, Puntschart, Kaijser, Jansson & Sundberg, 1999; Murrell et al. 2012).

II. Aerobic Exercise also has Cognitive Benefits

My research focuses on aerobic activity and working memory. Working memory is separate but complementary to short term memory and is defined as one's ability to process and store information (Alloway, 2010; Cowan, 2008). Short term memory is viewed as a simple storage buffer relating to practiced skills and strategies like rehearsal and chunking, where working memory is more complex and involves manipulating information (Baddeley, 2000; Baddeley & Hitch, 1974). Short term memory is also stored in areas of the frontal, parietal and temporal cortices (Butters, Nelson, Goodglass & Brody, 1970; Ojemann, 2004) where working memory is mainly found in areas of the prefrontal cortex (Jonides et al., 2008). Working memory has the ability to help maintain memory representations in the face of concurrent processing, distraction and attentional shifts (Engle, Kane & Tuholski, 1999).

The first working memory model proposed by Baddeley and Hitch (1974) attempts to address issues relating to the encoding and range of learning, comprehending and reasoning in the Atkinson and Shiffrin (1971) short term memory model. Baddeley and Hitch divide working memory into three distinct components which work together to help in the facilitation of complex cognitive tasks such as reading and how to use electronics. The main component of interest for my research is the central executive component and it is known for aiding in the control of attention while helping information flow to and from verbal and spatial short term memory buffers (Baddeley, 1986). The central executive system also helps with planning and navigating through the environment (Granon & Poucet, 1995). Additionally, this component plays a major role in the development of spatial mental models which is important for language comprehension, memory and route planning (Baddeley, Emslie, Kolodny & Duncan, 1998; Fitzgerald, 2011). The remaining two components are the phonological loop which helps with temporary storage of verbal and acoustic information and the visuospatial sketchpad manipulates visual information (Baddeley, 1992). More recently, Baddeley (2000) added an additional component, the episodic buffer, which also provides temporary storage and is capable of combining information from the subsidiary working memory systems as well as from long term memory.

The central executive component is most important for my research because it is where individual differences are found in working memory span tasks (Conway et al., 2005). Working memory span tasks have been used as a predictor in cognitive skills ranging from reading and arithmetic (Alloway & Copello, 2013), to control of selective attention, comprehension, reasoning, and problem solving (Baddeley & Hitch, 1974; de Fockert, Rees, Frith and Lavie, 2001). The central executive system has also been shown to decline with age (Baddeley, 1992). Moreover, age related decreases have been found in the visual resolution of working memory which is how visual information is stored in working memory (Peich, Husain, & Bays, 2013).

Based on evidence that working memory declines with age, it would seem reasonable to explore ways in which we can reverse this decline in working memory, or at least delay the age at which we begin to see change.

Aerobic exercise has been found to improve cognitive function in healthy adults (Kamijo et al. 2009; Sibley & Beilock, 2007). After aerobic exercise, increases in the P3 amplitude, a process that reflects neural activity and is related to attention and working memory, have been found in younger adults (Sibley & Beilock, 2007). Children also benefit cognitively from aerobic exercise. It provides children with the opportunity to acquire complex motor skills, as well as allows them to set and achieve goalsA (Best, 2010). Mahar et al. (2006) demonstrated a positive relationship between physical activity levels in elementary school children and on-task behavior (e.g., following class rules). On the other end of the fitness spectrum, an association between low aerobic fitness and childhood obesity was linked to poor academic performance, specifically relating to GPA, reading and math scores (Tomporowski, Lambourne, & Okumura, 2011).

Physical activity could be a key to helping cognitive function in both adults and children. In older adults, aerobic activity can improve brain function as they demonstrated increased volume in both gray and white matter primarily in the prefrontal and temporal cortices, both areas where age-related deterioration is usually found (Colcombe et al., 2006). Similar benefits from aerobic exercise may also be present in children as these brain regions have also been identified as being activated during mental arithmetic tasks, which require working memory and attentional resources (Rivera, Reiss, Eckert, & Menon, 2005). In fact, math scores on standardized tests were found to be positively related to exercise in school aged children (Grissom, 2005).

Benefits of cognitive function are mostly reported for an exercise session lasting only 20 to 40 minutes at sub-maximal aerobic intensity (Ellemberg & St-Louis-Deschênes, 2010). In a meta-analysis, Colcombe and Kramer (2003) reported fitness effects of cognitive function for older adults and found that aerobic exercise training increased cognitive performance one half of a standard deviation, on average, regardless of the type of task (speed, visuospatial, controlled processing and executive control), the training method (aerobic or combined cardiovascular and strength training, the amount of time per session and the duration of the exercise intervention) or participants' characteristics (age, sex or mental wellbeing). Sibley and Beilock (2007) found that aerobic exercise was most beneficial to adults with poor working memory: running for 30 minutes resulted in significant improvements in operation and reading span scores in the low-memory group.

Physical activity is also important in helping children achieve academic success. Neuro-imaging results from an exercise intervention lasting approximately three months indicated that children exposed to both the low (20 min/day) and high dose (40 min/day) exercise groups showed an increase in bilateral prefrontal cortex activity with a decrease in activity in bilateral posterior parietal cortex. The exercise intervention groups also had higher planning scores and mathematics achievement scores compared with to the control condition (Davis et al., 2011). Davis et al. (2007) tested the effect of aerobic exercise training on the cognitive functioning of overweight and sedentary children ranging from 7 to 11 years old. Results from the program indicated that the children in the high dose group (40 min/day exercise) increased their Cognitive Assessment Score for Planning by a one-third standard deviation using normal standardized scores compared to the no exercise control condition. These results demonstrate that aerobic exercise improves children's executive functioning capacity which is imperative to the development of one's imagination, creativity, and self-control. Tuckman and Hinkle (1986) reported results from a 12-week running program for middle school children and found that aerobic exercise not only improved children's creativity on the Alternate Uses Test which assessed flexible and divergent thinking but they out ran the control children and their pulse rates were much lower.

III. Running and Cognitive Benefits

Not all types of exercise may be equally beneficial to working memory. Pontifex, Hillman, Fernhall, Thompson & Valentini (2009) investigated the differences between aerobic exercise and resistance training on the executive control of working memory, reporting significant differences in participants' reaction time on a working memory task only after aerobic exercise but no significant differences in reaction time on the working memory task after resistance training. They concluded that aerobic exercise may be the only domain of exercise that is beneficial to improving cognitive functioning. Running, specifically, appears to have the greatest impact on working memory. Results from an optical imaging study comparing brain activation during times of walking and running revealed the most significant brain activation occurred during times of running at 9 km/h compared with walking at 3 and 5 km/h (Suzuki et al, 2004). One of the areas with the most prominent brain activation was the bilateral prefrontal cortices which is associated with working memory function. However, Lambourne (2012) found no significant differences between conditions on a random number generation task or an operation span task prior to, during, and after 35 minutes of cycling. These results indicate that running, as opposed to other types of aerobic exercises, may be the most beneficial with regard to increases in cognition.

Running has also been shown to activate the process of neurogenesis, which is the process of making new neurons. Creer, Romberg, Saksida, van Praag and Bussey (2010) found a link between running and the activation of neurogenesis in very aged mice. The mice ran on a wheel and then performed a spatial encoding task on a touch screen. Results indicated that running improved spatial touch screen performance when the stimuli were presented in close proximity. The authors suggested that running activated neurogenesis in these older mice, and these newly born neurons may have contributed to improvements in fine pattern separation and memory formation. One reason for why running can boost memory is because it changes catecholamine (dopamine, epinephrine, norepinephrine) levels in the brain as well as increases the amount of brain-derived neurotropic factor (BDNF) that is released (Brown et al., 1979: Winter et al., 2007). These neurotransmitters along with BDNF have been correlated with faster learning and better memory retention (Fitzgerald, 2011; Vaynman, Zing, & Gomez-Pinilla, 2004).

IV. Present Study: Barefoot Vs. Shod Running and Working Memory

In my study, I wanted to compare the effects of barefoot versus shod running on working memory. To date, the majority of research published about the differences in running shod or barefoot are more physiological rather than psychological (De Wit, De Clercq & Aerts, 2000; Divert, Mornieux, Baur, Mayer & Belli, 2005; Eslami, Begon, Farahpour & Allard, 2007; Stacoff, Nigg, Reinschmidt, van de Bogert & Lundberg, 2000). With 19.4% to 79.3% of runners reporting injury annually, it is important to understand the possible reasons why these injuries could be occurring (Van Gent et al., 2007). The most common site of injuries reported is the knee (42.1%), followed by the foot/ankle (16.9%), and hip/pelvis (10.9%) (Taunton et al., 2002). Kerrigan et al. (2009) found an increased external joint torque at the hip, knee, and ankle when running shod compared to barefoot, likely due to the raised heel of the typical running shod. It seems that the extra cushioning in running shod may decrease caution upon each landing which leads to an increased impact.

Barefoot running is one strategy that has been found to decrease injury and increase running time. In theory, the human foot has no need for additional external support and the idea is that the more time one spends running barefoot, the stronger the arch becomes (Rao & Joseph, 1992). Potthast, Braunstein, Niehoff and Bruggemann (2005) conducted a study using an MRI to show that foot muscle strength is affected by minimal footwear. Results indicated that the anatomical cross sectional areas of selected foot and shank muscle performance increased significantly with minimal shod in comparison to traditional footwear. Results from this study further support the idea that barefoot running enhances performance while decreasing injury.

Barefoot running has been shown to be more economical, with respect to oxygen consumption and heart rate, compared to shod running on both the ground and treadmill (Hanson, Berg, Deka, Meendering & Ryan, 2011). Several reasons have been posited for this phenomenon, including foot strike type (rear or forefoot), shoe cushioning, and force distribution (Shih, Lin & Shiang, 2013). Results from a ten week training study showed that individuals who transferred to barefoot running not only had faster two and three mile runs but they completed the 5k nearly thirty seconds faster than before while running shod (Baroody, 2013). Researchers contributed this difference to the participants' improved running economy.

Minimal shod runners have also been found to be more economical compared with traditional shod runners after shoe mass and stride frequency have been controlled for, regardless of strike type (Pearl, Daoud & Lieberman, 2012). The authors suggested that this difference may be due to the amount of elastic energy storage and release from the lower extremities during minimal shod running. Squadrone and Gallozzi (2009) found significantly shorter stride length and contact times and higher stride frequency with experienced barefoot runners compared with shod. Another aspect of greater efficiency is that barefoot runners demonstrate a trend for lower relative oxygen consumption (VO2) compared to shod because running with shoes require more energy (Hanson et al., 2011). One potential benefit of this is that runners have more oxygen to enable them to run longer distances.

We wanted to extend the research on the physiological benefits of barefoot running to explore potential cognitive gains as well. Specifically, we compared the effects of running shod versus barefoot on working memory performance. There are two possible factors that may contribute to gains in working memory performance when running barefoot. First, attention levels may be elevated because as you are running, you are forced to plan where you are stepping to avoid rocks, glass and other harmful objects that could cause injury to your feet. If you are constantly paying attention to where you are stepping, your brain is naturally more active than when running shod. We tested this premise by having participants step on targets (poker chips) that were strewn along a running track for both barefoot and shod conditions. Since participants were asked to step on as many targets as they could, it required them to pay more attention to the ground than they usually would, allowing them to plan ahead for their next steps.

The second possible contributing factor is greater efficiency in oxygen consumption. The idea is that running barefoot conserves one's oxygen resources which would allow one to run for a longer period of time (Hanson et al., 2011). In our study, we measured participants' heart rate as a linear relationship exists between oxygen uptake (VO2) and heart rate. Thus, a decreased heart rate while running may be indicative of more economical oxygen consumption, which could led to faster running times or longer running distances. In the present study, numbers of laps was used as an indicator running efficiency.

We recruited exercise science majors who typically ran at least two miles in a single session. They ranged in age between 18 and 22 years and all were in good physical condition, capable of running for the required amount of time (8 minutes) at each session, for barefoot and shod conditions. Our study is beneficial to the expanding literature because barefoot running may be a more efficient way to gain aerobic activity, as well as one that has the potential to yield greater cognitive benefits in adults. In our study, we recruited young adults as there is relatively less research aimed at this population as they may be performing at peak cognitive levels. It may be that the potential cognitive gains of running; specifically barefoot running are limited when participants are at their maximum cognitive capacity.

Method

Participants

There were 73 exercise science majors (45% males) from the University of North Florida who volunteered for this study, in exchange for extra credit. All participants were between the ages of 18 and 22; of those who responded, 1% were sophomores, 75% juniors, 4% seniors, and 3% graduate students. Of the respondents, 64% were Caucasian, 3% were African American, 6% were Latin, and 8% were Asian.

The participants can be classified as individuals who exercise recreationally and ran more than 2 miles per occasion. None of the participants reported running barefoot before the study. When asked about regular physical activity, 79% reported attending the gym during the week engaging in a range of activities, including cardiovascular machines, like treadmills, using weights (free weights and machine), as well as cross fit and other group fitness activities (21% did not report any activity). The average engagement of physical activity was three times per week, with an average of 57 minutes per workout session (SD = 36.61, min = 15 mins, max = 180 mins). Based on the information of the Health History Questionnaire 26 % responded with health related concerns, the main areas of health concern were asthma (6.9%) and pain in knee, shoulder and joints (11.2%).

Materials

Working Memory

Working memory was measured using modified version of Backward Digit Recall taken from a standardized assessment, the Alloway Working Memory Assessment-II (AWMA-II; Alloway, 2012). The individual recalls a sequence of spoken digits in the reverse order. The test begins with recalling two numbers in backward order and is increased by one item in each block, up to nine numbers per block. There were two trials in each block and the number stimuli were randomized for the different testing phases. Scoring was calculated based on the highest block (span) where they correctly recalled one of the two trials.

Health History Questionnaire (HHQ):

Each participant was given a pamphlet of information about working memory, as well as an explanation of procedures, objectives and potential risks that one may face during the study. Participants were assured that all data obtained would remain confidential. They were also reminded that they could drop out of the study at any time with no penalty. The HHQ that participants were to fill out pertained to gym activities or other activities that one would engage in during exercise sessions. We asked participants to list any previous medical conditions or medications that the researchers should be aware of before the start of the study.

Running condition

Each participant completed two days of testing, with two sessions per day. Running condition was counterbalanced for barefoot (no socks, no vibrams/ minimalist running shoes) and shod (shoes; no vibrams/ minimalist running shoes) on both days. Participants ran around a 200-meter track for eight minutes. After each lap, the experimenter recorded participants' running time and heart rate. Testing Day 1 differed from Testing Day 2 in only one respect: on Day 1 (Target condition), participants were instructed to step on targets, which were 200 poker chips placed at random locations within the running lane spaced approximately one meter apart. Participants recorded the number of targets they missed using a clicker and reported that to the experimenter. Participants were instructed to run in a single lane but were allowed to pass another runner so they were running at a comfortable self-selected pace. On Day 2 (No Target condition), participants were only instructed to run in a single lane but were allowed to pass another runner so they were running at a comfortable self-selected pace. There were no targets (poker chips) placed on the running track.

Procedure

When the participant arrived, they first completed the Health History Questionnaire. They were then given a heart rate monitor that they strapped to their chest. Participants sat down for a few minutes and then reported their pre-exercise heart rate to the experimenter. Next, they completed a working memory test. The experimenter called out a sequence of numbers and participants recalled them in backwards order. This initial test provided a baseline for the participants' working memory. The participants then ran for eight minutes; either barefoot or with shoes, depending on the condition they were assigned (counterbalanced within-group).

Participants then walked back to the testing area and were given the working memory test, with a new set of numbers which they recalled backward. Participants then switched running conditions (barefoot or shod) and ran for a further eight minutes. They walked back to the testing area where they were given the working memory test with a new set of numbers which they recalled backward.

Scoring

Running intensity was measured as the participant's average Heart Rate from Lap 2 to final lap for each eight-minute period. Lap 1 was used as a warm up lap to ensure participants were running at a comfortable pace and allow time for any adjustments that needed to be made that may have affected their running performance. ***Distance*** was measured by meters ran per session. At eight minutes, participants were told to stop running and depending on where they stopped on the track we calculated their last lap as ¼ (50 meters) through 1 lap (200 meters) and added that number to total laps ran per session. Self-selected pace was measured as the distance in meters over time (8 minutes). ***Accuracy*** was measured by the amount of targets (poker chips) they missed during each running session using a clicker.

Results

Working Memory

In order to compare the effect of running on working memory, we first conducted a mixed measures Analysis of Variance (ANOVA) on the Target condition with working memory sessions (baseline, session 2, session 3) as the within-subject variable and running condition (BF first; shod first) as the between-subject variable. There was a significant main effect of working memory performance across the testing sessions, F (2,140) = 3.95, p = .021, $\eta 2p$ = .053; and Running conditions, F (1, 70) = 10.07, p = .002; $\eta 2p$ = .128. However, the interaction was not significant, *F* (2,140) = 2.32, *p* = .12. Pairwise comparisons of working memory scores indicated improvements only between the Baseline and Session 3 (*p*<.05).

The next mixed measures ANOVA was based on the No Target condition with working memory sessions (baseline, session 2, session 3) as the within-subject variable and running condition (BF first; shod first) as the between-subject variable. There was no significant main effect of working memory performance across the testing sessions, *F* (2,130) <1, *p* = .40; nor for Running conditions, *F* (1, 65) <1, *p* = .79. There was also not a significant interaction, *F* (2,130) <1, *p* = .64.

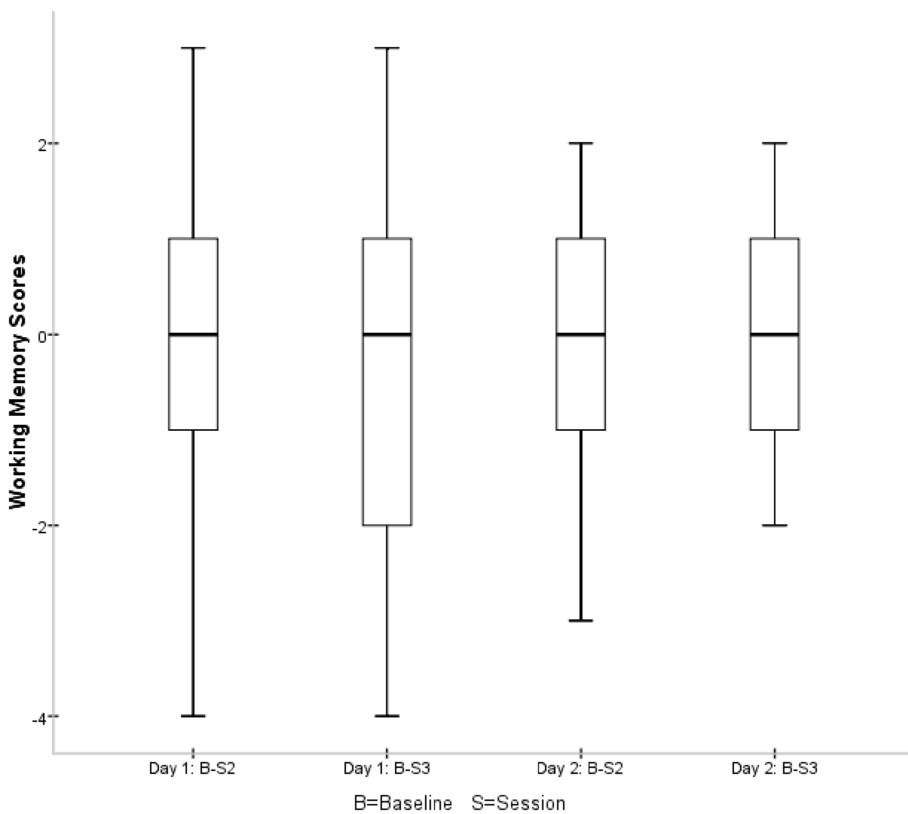

Figure 1. Working Memory scores as a function of Day (Targets or No Targets) and Session

To determine participants' cognitive gains as a function of training, we subtracted the Baseline (Session 1) working memory scores from the Session 3 working memory scores and compared the difference in scores as a function of running condition (BF vs shod). Figure 1 demonstrates the difference in scores between these two groups as a function of Target conditions: Target (Day 1) versus No Target (Day 2). We conducted independent t-tests only for the Target condition with Running condition as the independent variable because there were no significant differences found in the No Target condition. When the group ran BF last, they demonstrated significant working memory improvements between the Baseline (Session 1) and Session 3: t (70) = 1.96, p = *.05*, d = .462; but not when they ran Shod last, t (70) = 1.36, p = .18. This pattern of improvement suggests that barefoot running can be beneficial to working memory performance. This difference is only evident when participants' had to hit a target as they ran.

Physiology

Next, I wanted to investigate the relationship between the physiological measures (Heart rate & Speed) and Target Accuracy; on Running and Working Memory.

Table 1

Means and Standard Deviations of Heart Rate, Aerobic Deficit and Self-selected pace as a function of Running Style (BF or Shod) and Day (Target or No Target)

	Heart Rate		Aerobic Deficit		Self-selected pace	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Day 1						
BF	170.87	18.07	9.77	16.29	121.14	16.94
Shod	167.55	19.05	7.65	17.01	117.37	16.12
Day 2						
BF	169.66	14.54	19.01	14.26	172.06	26.22
Shod	167.13	13.73	15.66	7.90	172.06	23.96

Heart Rate

In order to compare the effect of running on heart rate, a repeated measures ANOVA was conducted for participants' average heart rate from Lap 2 to their final lap. There was a significant main effect of Shoe condition (BF vs shod), $F(1, 65) = 4.80$, $p = .03$; $\eta 2p = .069$. However, there was no main effect of Target condition: $F(1, 65) < 1$, $p = .62$; and the interaction was not significant $F(1, 65) < 1$, $p = .76$. Participants' heart rate was significantly lower when running shod across Target conditions compared to running barefoot. Post hoc analyses confirmed a trend towards higher heart rate in the barefoot condition compared to shod, when there were no targets (Day 2) $t(67) = 1.76$, $p = .08$, but not when they were hitting targets (Day 1) $t\ (70) = 1.30$, $p = 1.99$. These results indicate that running shod decreases participants' heart rate when they run at a self-selected pace without targets.

Heart Rate Deficit

We also investigated differences in heart rate deficit, which was calculated from Heart Rate at Lap 1 before achieving a steady state (the average Heart Rate from Lap 2 to their final lap). A repeated measures ANOVA conducted on a participants' heart rate deficit indicated no main effect of Shoe Condition (shod vs BF): $F\ (1, 59) = 2.12$, $p = .15$. However, there was a main effect of Target condition, $F\ (1, 59) = 25.069$, $p<.001$; $\eta 2p = .298$. But the interaction was not significant $F\ (1, 59) = <1$, $p = .73$. Post hoc analyses confirmed that participants' achieved their optimal heart rate faster when they were running with targets in both the BF condition $t(63) = 3.66$, $p = .001$, $d = .60$ and the shod condition $t(62) = 3.63$, $p = .001$, $d = .60$.

Self-selected Pace (Distance / Time)

A repeated measures ANOVA conducted on self-selected pace indicated no main effect of Shoe Condition (shod vs BF): $F\ (1, 67) = 1.69$, $p = .198$. However, there was a main effect of

Target condition, F (1, 67) =447.89, p<.001; η2p=.870, but the interaction was not significant F (1, 67) =3.43, p=.068. Post hoc analyses confirmed that participants' self-selected pace was significantly slower when they had to hit targets compared to not hitting targets in both the BF condition t(67)= 18.03, p<.001, d=2.31 and the shod condition t(67)= 21.39, p<.001, d = 2.68.

Target Accuracy

We also looked at the percentage of participants' missing targets while running barefoot versus shod and removed two outliers from the data set (>3 *SD* from sample mean, one in each shoe condition). A paired samples t-test indicated that there was no significant difference in the percentage of misses when running barefoot (*M*= 4.75, *SD*= 4.53) versus shod (*M*= 4.00, *SD*= 3.97), t (70) = 1.44, p=.154.

Working Memory & Physiology

We were also interested in how physiology may mediate the effects of running condition on working memory performance. We first conducted correlation analyses separately for each running condition only for Day 1 (Target condition) only. Table 2 represents the relationship between Working Memory and shoe condition across speed, average heart rate and heart rate deficit on Day 1.

Table 2

Correlations of Working Memory and Running conditions across speed, HR & HR Deficit for Day 1

	Working Memory Score	Speed	HRAvg_Lap2_9	HR Deficit
Working Memory Score	1	0.108	-0.034	0.132
Speed	-0.061	1	.009	-.223
HRAvg_Lap2_9	0.347	0.093	1	-0.642*
HR Deficit	-0.162	-0.021	-0.539*	1

Note. Correlations for participants running barefoot are presented above the diagonal, and participants running shod are presented below the diagonal.
* $p < .01$ (2-tailed).

These results are an indication that average heart rate (lap 2- final lap) is significantly associated with working memory improvements (Baseline -Session 3) only for the BF condition, not the Shod condition for Day 1 when participants had to hit targets.

To follow up on this finding and investigate whether heart rate was mediating the earlier effect of running condition on working memory performance, we reran the mixed measures ANCOVA, this time controlling for Heart-Rate in both the barefoot and shod conditions. Working memory sessions (baseline and session 3) were the within-subject variable and running condition (BF first; shod first) was the between-subject variable. There was a trend towards significance for working memory performance across the testing sessions, F (1, 66) = 3.35, p = .07, η2p = .048; and Running conditions, F (1, 66) = 8.59, p = .005; η2p = .115. The interaction between working memory sessions and running condition was significant, F (1, 66) = 8.20, p = .006, η2p = .111. The interaction between working memory sessions and Heart Rate for running barefoot last was also significant, F(1,66) = 6.94, p = .01, η2p =.10. However, the interaction between working memory sessions and Heart Rate for running shod last was not significant, F (1,66) = 1.45, p = .23. This means that without taking heart rate into account, running condition still played a significant role in working memory scores (baseline and session 3) regardless of running barefoot or shod first. When heart rate was taken into account, running barefoot last revealed significant improvements in working memory compared with running shod last which showed no differences in working memory.

Discussion

There were a few main findings that stemmed from this investigation. The first is that working memory performance increased in the barefoot condition when participants hit targets while running. This result supports the idea that additional attention is needed when running barefoot to avoid stepping on objects that could potentially cause harm to the foot which may have activated participants working memory as a result. Previous researchers have supported the idea that the central executive component is involved in the development of spatial mental models and planning which allows for adequate navigation through the environment (Baddeley, Emslie, Kolodny & Duncan, 1998; Fitzgerald, 2011). Participants were engaging in the skill of route planning such that they had to plan ahead for their next steps and in the moment strategize an efficient route for hitting as many targets as possible. Additionally, the level of attention that is needed while running barefoot helps ones working memory to focus solely on information that is relevant to the task at hand and to inhibit or filter out irrelevant information; which may be another reason why we found significant improvements in working memory scores (Tomporowski, 2003).

However, significant increases in working memory scores were only found after participants ran for at least 16 minutes but not after eight minutes. It seems that increases in working memory performance are only significant roughly between fifteen minutes and thirty minutes of aerobic exercise. Results from a meta-analysis revealed no significant difference in short term memory scores after 4 minutes of running or during 6 minutes of cycling (Tomporowski, Ellis, & Stephens, 1987; Sjöberg, 1980). However, longer bouts of aerobic exercise can increase cognitive functioning. For example, Sibley, Etnier and Le Masurier (2007) found 20 minutes of treadmill running improved performance in a cognitive inhibition task, which together with working memory, falls under the umbrella of executive function skills. Heckler and Crace (1992) also found that "less fit" women were able to solve math problems significantly faster after 20 minutes of treadmill running.

Heart Rate

Results relating to the physiological aspects of the study revealed an increase in heart rate in the barefoot condition, contrary to what was expected. However, there are many kinematic differences between running shod and barefoot that should be taken into consideration. The biggest difference occurs at the initial phase of locomotion where the barefoot runner initiates contact with the forefoot or midfoot and the shod runner with the rear foot (Lohman, Balan Sackiriyas & Swen, 2011). This difference in barefoot running causes a flatter foot placement while reducing the amount of impact on the heel as it touches the ground (De Wit, De Clercq & Aerts, 2000). Since participants had never engaged in barefoot running before, it is likely that they had to overcompensate for these differences by working harder while running barefoot; causing their heart rate to increase. According to Lieberman, Venkadesan, Daoud, & Werbel (2010), it could take up to a few months to build up the muscles in the foot to be able to successfully run barefoot without causing injury. Thus, the increase in participants' heart rate in the present study fits with the novelty of barefoot running.

Speed

The last major finding from this investigation is that there was no difference in participants speed between barefoot and shod conditions or target versus no target condition. One reason for this is that we told participants to run at a self-selected pace. Since participation in this study required individuals to run at least two miles per occasion on a regular basis, participants had already established a comfortable pace at which they liked to run, both barefoot and shod.

Future Directions

"Barefoot running has been touted as improving strength and balance, while promoting a more natural running style" (American Podiatric Medical Association, 2014). In addition, barefoot running allows us to be close to nature, while improving cognitive functioning.

While the present study focused on immediate gains in working memory scores, future researchers can also investigate the persistent of such gains, and its potential impact to long-term knowledge such as long term memory, increases in academia relating to reading, writing and arithmetic (Grissom, 2005; Rivera, Reiss, Eckert, & Menon, 2005). Past researchers that have focused on changes in amounts of neurotransmitter and brain-derived neurotropic factor released in the brain while running suggest that running may have longer-term benefits and should be studied further (Brown et al., 1979; Fitzgerald, 2011; Vaynman, Zing, & Gomez-Pinilla, 2004; Winter et al., 2007).

The cognitive benefits of barefoot running can be useful for different populations. Older individuals who are at the highest risk for developing dementia or Alzheimer's may find barefoot running useful in delaying symptoms of memory loss. Increases in barefoot running can help provide the neural substrates of the aging brain with a degree of flexibility and plasticity to compensate for the negative effects of aging. The United States Census Bureau (2010) reported an estimated 40.3 million individuals living in the United States over the age of 65 and trending upward. With such a dramatic increase in the elderly population, it is important to find ways in which we can help delay cognitive deterioration, and barefoot running is one of them. Future studies can compare the effects of barefoot running on elderly individuals with and without signs of cognitive deterioration to confirm the potential gains in cognition. However, caution should be taken to ease into any new aerobic activity.

Individuals who are less fit can also benefit by running barefoot. Researchers suggest that 32 to 60% of adults were reported as being overweight in the United States, with 4% considered to be extremely obese (Ogden et al., 2006). Obesity in America is on the rise and contributes to many health problems including depression, type 2 diabetes, cardiovascular disease, stroke and early fatality (McCue, 1981; Wyatt, Winters & Dubbert, 2006). Not only will individuals who are less fit benefit cognitively but it may help change their lifestyle and act as a preventative to developing life threatening diseases. Future studies should be conducted using a control condition and experimental condition of less fit individuals who will engage in a long term exercise regime, incorporating barefoot running to compare the effects of running barefoot over a long period of time.

Lastly, children who are behind, academically, may find that barefoot running helps them receive the additional assistance they need to catch up to the rest of their peers. Since children are still developing both physically and cognitively, barefoot running may also help prevent obesity and other problems that come with living a sedentary lifestyle early on. It addition, it may be easier for children to make the transition to running barefoot since their feet have not fully adapted to running shod.

In conclusion, results from our study suggest significant increases in working memory after approximately 16 minutes of barefoot running. Since individuals have to pay more attention to what they are stepping on when running barefoot, their brains may be naturally more active, causing a boost in working memory. Heart rate was also higher when running barefoot compared to shod but this may have been due to the fact that participants in our study had no previous experience with barefoot running, forcing them to work harder, which led to an increase in heart rate. However, even after controlling for increases in heart rate, barefoot running still resulted in significant increases in working memory performance. After one makes the transition to running barefoot and their feet muscles have adapted, it is expected that heart rate will be lower than when running shod, adding another health benefit and reason to run barefoot.

Vita

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