NONLINEAR HEMODYNAMICS OF WORKLOAD AND WORKLOAD TRANSITIONS

by

Ryan D. McKendrick
A Dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Psychology

Committee:

____ Director

____

____

____ Department Chairperson

____ Program Director

____ Dean, College of Humanities and Social Sciences

Date: ______________________________ Spring Semester 2016
George Mason University
Fairfax, Virginia

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By

Ryan D. McKendrick
Master of Arts
George Mason University, 2013
Bachelor of Arts
Rutgers University, 2009

Director: James Thompson, Professor
Department of Psychology

Spring Semester 2016
George Mason University
Fairfax, VA

DEDICATION

This work is dedicated to my wife Liliya, my two children Sophia and Charlie, my parents Don and Judi, my brothers Kyle and Todd, and my mentor Raja Parasuraman. Through you I received the inspiration and perseverance needed to complete this work.

ACKNOWLEDGEMENTS

I would like to thank the many friends who have influenced and assisted me in my work. Especially my friend William Miller for his continuous MATLAB assistance. Finally, thanks go out to my committee, Drs. Thompson, Shaw and McKnight for their invaluable help and insight.

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ABSTRACT

NON-LINEAR HEMODYNAMICS OF WORKLOAD AND WORKLOAD TRANSITIONS

Ryan D. McKendrick, Ph.D

George Mason University, 2016

Dissertation Director: Dr. James Thompson

Quantifying and classifying cognitive load (i.e. how individuals cognitively respond to the demands of a task) is important for optimal performance. How cognitive load changes over time (i.e. workload transitions) alters the perception of cognitive load and performance. Activity in prefrontal cortex has previously been associated with working memory load. Furthermore, attenuation of prefrontal activity has been linked to cognitive overload, a cognitive load state associated with failures in task performance. We hypothesized that a similar nonlinearity would be observed for cognitive underload, a cognitive load state associated with mind wandering and inefficient attention strategies. These two nonlinearities for cognitive underload and overload would manifest as a cubic function in lateral prefrontal cortex relating to working memory load. Observation of this function would allow for objective classification of different cognitive load states. These states could then be identified in individual performers and used to study the effects of

workload transitions to different cognitive load states. Workload transitions were hypothesized to induce an increase in cognitive load as indexed by changes in oxygenated hemoglobin in lateral prefrontal cortex.

Two studies were conducted. The first study assessed the relationships between working memory load and subjective, behavioral and hemodynamic measures of cognitive load. Individuals performed a spatial working memory task, experiencing a range of working memory loads from very easy (one object) to very hard (ten objects). A cubic function was observed in left lateral orbitofrontal cortex (LLOFC) relating working memory load to changes in oxygenated hemoglobin (HbO). However, the shape of the relationship was not as hypothesized. Incorporating the hemodynamic and behavioral effects suggested that attenuation of prefrontal activity is associated with performance enhancing compensatory mechanisms and a later facilitation of activity is associated with cognitive overload.

Using the function observed in LLOFC as an index for different cognitive load states, a second study tested the effects of workload transitions to different cognitive load states. In an initial session we replicated the effects observed in study one and used these effects to identify cognitive load states in individual performers. In a second session the effects of transitioning to different cognitive load states were assessed. These transitions had little effect on subjective and behavioral measures of cognitive load. However, cognitive load state transitions did cause a deviation between behavioral measures and induced a significant change in the cubic function relating LLOFC HbO and working memory load.

We conclude that changes in cognitive load cannot sufficiently account for workload transition effects on behavior and prefrontal activity. Instead, to account for our effects and their deviation from previously observed effects, we present a preliminary hypothesis associating workload transitions with disruption of cognitive process integration and an increase in cognitive satisficing.

INTRODUCTION

Humans are capable of complex and amazing skills. The acquisition of skills can be accelerated and skilled performance enhanced by adapting training and activities to the mental needs of the individual (Chandler & Sweller, 1991). In the context of performance and skill acquisition, mental needs or cognitive load refer to the amount of mental work an individual is doing relative to the amount of mental work an individual is capable of (Parasuraman, Sheridan & Wickens, 2008). Therefore, cognitive load is related to task difficulty. However, the two concepts are not equivalent. Task difficulty refers to properties of a task which when manipulated are expected to affect performance. Cognitive load is a property of an individual performing mental work. In many cases the two concepts are linked; increases in task difficulty result in increases in cognitive load. However, this is not necessarily the case, some tasks are difficult because they place high demands on physical strength, or perceptual acuity. Such tasks do not necessarily produce high cognitive load. Conversely, tasks that are difficult because they require attending to multiple things simultaneously, or holding many things in memory, are difficult and induce high cognitive load.

Traditionally different levels of cognitive load are compared as if they are temporally independent. Specifically, it is assumed that counter-balancing or randomizing task demand levels removes any effects that one level might have on another However, cases where workload levels are not temporally related rarely occur during real cognitive work. For example, an air traffic controller doesn’t monitor the same number of planes, moving at the same air speed and similar trajectories throughout a supervisory period. Instead the number of planes, their speed, flight trajectories and even the weather conditions regularly change creating a temporally dependent cognitive load environment. It follows that measurement of the effects of temporally dependent and dynamic cognitive load are needed to improve performance prediction. When cognitive load changes from one load level to another, this is referred to as a workload transition; as cognitive load has transitioned from one load at a specific time to a new load at a new time. As mentioned, workload transitions are common in a variety of settings such as commercial and public airtraffic control and aircraft operation, commercial and public railway operation, nuclear power plant operation, military tank operation, military and merchant shipping operation, search and rescue, emergency medical services, and the medical operating room (Huey & Wickens, 1993). An improved understanding of workload transitions can improve the utility of workload models in explaining and predicting human errors. Improvements in our understanding of workload transitions will also improve the application of automated aiding in improving human-machine system performance.

Effects of Workload Transitions on Behavior

The direction of workload transitions (i.e. increasing or decreasing cognitive load) produced mixed evidence regarding their effects on task performance. A number of studies have found that workload transitions negatively impact performance. For example, a seminal investigation tested the effects of incrementally increasing event rate followed by incrementally decreasing event rate in a number shadowing task. Decreasing event rate produced a decrement in performance (Cumming & Croft, 1973)., while studies of an abrupt increase in event rate have shown reduced signal detection performance (Krulewitz, Warm & Wohl, 1975). Furthermore, when required to accurately identify the accuracy of a numeric expression, as well as respond as quickly as possible, random changes in task demands increase reaction time and decrease response accuracy (Mathews, 1986). In general, transitioning to lower task demands decreases task performance (Thorton, 1985; Mathews, 1986; Hancock et al., 1995; Cox-Fuenzalida et al., 2004; Cox-Fuenzalida et al., 2005; Cox-Fuenzalida et al., 2006; Cox-Fuenzalida, 2007; Bowers et al., 2014), and transitioning to higher task demands degrades task performance as well (Kreulewitz et al., 1975; Hancock et al., 1995; Cox-Fuenzalida et al., 2004; Cox-Fuenzalida et al., 2005; Cox-Fuenzalida et al., 2006; Cox-Fuenzalida, 2007). However, it should be kept in mind that this is not a decrement in performance relative to different task demands. Even in the presence of workload transitions really high task demands still produce lower performance relative to low task demands. The effect of workload transitions is that transitioning to low task demands from other task demands produces inferior performance relative to if low task demands had occurred throughout the same time period. Counterintuitively there is also evidence that transitions to lower task demands induces a greater relative decrements than transitions to higher task demands (Cox-Fuenzalida et al., 2006).

Observations of negative effects following workload transitions are the best supported, however there is a considerable body of evidence showing positive effects of workload transitions. Incrementally increasing event rate during number shadowing resulted in monotonic improvements in task performance (Cumming & Croft, 1973). When not asked to accurately identify numeric expressions, but only respond to them as quickly as possible random and incremental increases in task demands increased the speed of response (Mathews, 1986). Other studies involving number shadowing and air traffic control simulations have replicated the positive effects of incremental increases in task demands (Goldberg & Stewart, 1980; Schaab, 1999; Farrel, 1999). Improvements have also been observed during abrupt workload transitions. During a simulated driving task, drivers maintained better vehicle control following a systems navigation failure (Morgan & Hancock, 2010). Similar improvements during abrupt increases in task demands have also been observed in compensatory tracking, and logic gate (MATB resource management) tasks (Bowers, Christensen & Eggemeir, 2014). Overall the effects of workload transitions on behavior are inconsistent but the largest amount of evidence suggests they are detrimental to task performance. It is highly likely that observed inconsistencies in effect are due to methodological inconsistencies.

Effects of Workload Transitions on Subjective Measures

Subjective report of cognitive load (e.g. 'how mentally demanding was this task?') is also effected by workload transitions. Subjective workload can be effected by workload transitions in at least two ways. There can be resistance to changing perception of cognitive load (Morgan & Hancock, 2010), this is known as hysteresis, or a distorted exaggeration for changing the perception of cognitive load, this is known as relativistic. Hysteresis effects were observed during a driving simulation when workload transitioned from low cognitive load to high cognitive load as a navigation system failed, and reverted to low cognitive load once the failure was remedied. Subjective workload after the navigation failure remained high, similar to that reported during the failure and higher than that reported prior to the failure (Morgan & Hancock, 2010). Relativistic effects have been reported in basic psychomotor tracking tasks. When high cognitive load transitioned to low cognitive load participants reported the task as easier than when the low cognitive load was experienced without transition. The opposite was observed when the transition was to high cognitive load; even higher cognitive load was reported (Hancock et al, 1995).

The within and between individual effects of workload transitions on subjective workload can moderate task performance in different ways. When task demands increase an individual’s perception of a task’s average cognitive load (workload trait response), transitions have a more detrimental effect on task performance. Furthermore, the higher an individual’s perception of workload at a given time (workload state response) the more sensitive that individual’s performance is to cognitive load transitions (Mracek et al, 2014). Specifically, there are greater linear decreases in performance following a transition to higher cognitive load, and greater linear increases following a transition to lower cognitive load. The quadratic effects following transitions follow the same pattern as the linear effects. Namely, if cognitive load increases the quickening of the negative effect on performance is greater when subjective workload is higher, and the inverse is true when demands decrease (Mracek et al, 2014). To reiterate, the higher an individual's subjective workload state the more sensitive they are to subsequent changes in cognitive load.

Subjective reports of workload are also sensitive to when an individual is queried relative to when and how often cognitive load transitions occur. When transitions are common and random in terms of their direction and magnitude, subjective workload assessed at the end of a trial follows the average of the workload conditions presented (Yen et al., 1985). However, if the transitions are seldom, and occur at specific time points, the report of subjective workload is biased. The closer in time the transition occurs relative to the subjective workload query the more influence the cognitive load transition has on the report of workload (Thorton, 1985).

Shortcomings of Previous Workload Transition Studies

Previous workload transition research has suffered from a number of inadequacies. For example, inadequate task selection has hindered the generalizability of findings. Non-adaptive task demand assignments can reduce the construct validity of workload transition studies because identical task demands can cause different cognitive states in different individuals. Finally, a lack of objective cognitive load measurement hinders adaptive task demand assignment and the generalizability as well as explanatory power of research observations. Each of these three indictments will be elaborated upon in the sections that follow.

Strong Concepts for Manipulating Cognitive Load

It is common place to use complex or applied tasks (Hanckock et al., 1995; Morgan & Hancock, 2010; Mracek et al., 2014) when studying workload transitions. Without a strong theoretical framework for workload transition effects, generalizing observations from one applied task to another applied task can be difficult. When basic tasks have been used they are predominately signal detection tasks, where cognitive load is manipulated via event rate. Event rate as a manipulation of cognitive load is problematic because it cannot change instantaneously. Therefore, as individuals' transition from one event rate to another they will necessarily be exposed to intermediary event rates between the current and target event rate.

As a construct for studying workload transitions, working memory offers a number of advantages over complex tasks and signal detection tasks. Working memory refers to a limited capacity store (be it a unique buffer or part of long term memory) (Logie, 2011; Baddeley, 2012) that works in conjunction with a cohort of executive functions (Unsworth & Engle, 2007). Working memory capacity (WMC) is predictive of performance on a number of complex cognitive tasks. Specifically, individuals with high WMC exhibit superior visual attention (Engel, 2002), inhibition of irrelevant representations (Unsworth & Engle, 2007), improved time critical decision making (Endsley, 1995) and enhanced supervisory control of unmanned aerial vehicles (de Visser et al., 2010; McKendrick et al., 2014)**.** Individuals with greater working memory capacity also store more task relevant information and recall that information more quickly. High working memory individuals also update information more efficiently, shift and maintain tasks goals with less error, and better cope with distractions (Unsworth & Engel, 2007). Furthermore, working memory difficulty can be discretely manipulated where the difficulty of one trial does not inherently affect the difficulty of a subsequent trial. The theoretical underpinnings of working memory, specifically its predictive power for basic and complex tasks and its property of instantly affecting cognitive load make it a prime concept for studying workload transitions.

Task Demand Adaptation is Important for Construct Validity

Except in one case (Bowers et al., 2014), workload transition studies have made no attempt to adapt task demand manipulations to individuals. Without adaptation, individual differences in cognitive capacity can result in different levels of cognitive load in different individuals even when task demands are identical. When workload transitions to different levels of an ‘optimal’ cognitive load state (cognitive demands do not exceed cognitive requirements) a lack of adaptation has minimal confounding effects. However, if workload transitions cause some individuals to transition out of an ‘optimal’ cognitive load state and into an overload or underload state a lack of individual adaptation is problematic for assessing workload transition effects.

The examination of overload and underload is important because these workload states have the greatest effect on task performance. While different levels of an ‘optimal’ cognitive load state should elicit positive task performance, both overload and underload are likely to elicit inferior task performance. The overload state should result in errors related to an inability to process more, or new information, leading to individuals being unable to cope with, current, future or the cognitive demands of a new task (Parasuraman et al, 2008). The underload state which is believed to be as detrimental (Hancock & Parasuraman, 1992) and more difficult to measure than overload (Hancock & Verwey, 1997) appears to induce its own unique task decrements. Specifically, underload induces boredom, passivity, mind wandering or other compensatory strategies and inefficient use of relevant task strategies. (Young & Stanton, 2002a; Young & Stanton, 2002b). In order to address issues of workload transitions into overload and underload it is necessary to adapt task demands on an individual basis. Furthermore, given that cognitive load and task performance are not equivalent (Parasuraman et al, 2008) other objective measures of cognitive load are required.

Objective Measures of Cognitive Load are Needed

While subjective measurement of workload is sensitive to the effects of workload transitions it is not without fault. Specifically, subjective measurement is invasive in that measurement interrupts the task being performed. If measurement occurs after the task is completed the most recent task demands weight the heaviest on the report (Thorton et al., 1985). Another method for measuring cognitive load is via measurement of mental resources, the fuel that allows for cognitive processing (Parasuraman & Rizzo, 2008). Neuroimaging allows for objective non-invasive measurement of mental resources during variable task load.

Linear effects of Cognitive Load on Objective Measures of Workload

Multiple studies looking at the parametric effects of working memory load have found consistent increases in the blood-oxygen-level dependent (BOLD) contrast in dorsolateral prefrontal (DLPFC) and posterior parietal cortical (PPC) regions of the brain (Braver et al., 1997; Cohen et al., 1997; Culham et al., 2001). Increases in oxygenation (Oxygenated– Deoxygenated hemoglobin) as measured with functional near infrared spectroscopy (fNIRS) have also been observed during increasing memory load (Ayaz et al., 2012). Examinations of increases in memory load with EEG have shown an increase in frontal midline theta (4hz to 7hz) power and a decrease in slow (8hz to 12hz) alpha power (Gevins et al., 1997; Meltzer et al., 2007). Similar BOLD changes in DLPFC have also been found when task difficulty increases by comparing single tasks to dual-task paradigms (Szameitat et al., 2002; Jaeggi et al., 2003).

fNIRS has also been used to measure the effects of cognitive load in complex tasks. In a supervisory control task where memory load was manipulated via the number of aircraft to be supervised, oxygenation in DLPFC increase with the number of aircraft. Similarly, during a natural orifice translumenal endoscopic surgery (NOTES) simulation experienced NOTES surgeons showed increases in oxygenated hemoglobin in bilateral ventral lateral prefrontal cortex when the simulation required a more difficult navigation path through an orifice (James et al., 2011). Taken together there is strong evidence to suggest that changes in cognitive load can be observed via monitoring of lateral prefrontal brain activity.

Nonlinear Effects of Cognitive Load on Objective Measures of Workload

A linear relationship between task workload and hemodynamics is often observed (Braver et al., 1997; Cohen et al., 1997; Culham et al., 2001; Ayaz et al., 2012), but it should be noted that the relationship is not always linear. In a PET study dual-task (wisconsin card sort paired with verbal shadowing) DLPFC activation was significantly lower compared to activation during the single tasks. This minimally suggests that DLPFC activation is attenuated by increasing cognitive load (Goldberg et al, 1998). This was directly observed during an n-back task where excessive load induced a negative quadratic (inverted u) relationship between memory load and BOLD response (Callicott et al., 1999). A non-linear trend has also been observed during supervisory control tasks (Durantin et al., 2013). Individuals navigated remotely operated vehicles (ROVs) through an airspace while avoiding no fly zones. Cognitive load was manipulated by altering crosswinds, vehicle inertia and memory load regarding supervisory control. Oxygenation had a negative quadratic relationship with increasing demands of vehicle control and memory load in bilateral DLPFC. A strong correlation between increased DLPFC oxygenation in the highest workload condition and performance was also observed. This relationship suggests that workload alone does not have a quadratic relationship with functional hemodynamics, but instead supports the attenuation hypothesis, where cognitive overload induces reductions in hemodynamics (Durantin et al, 2013). Evidence from two other studies support this claim. In a modified version of ‘rock, paper, scissors’ against a computer, cognitive load was manipulated by decreasing the inter stimulus interval (ISI). Furthermore, these decreases were adapted to each participants minimum effective ISI. When cognitive load was manipulated as a function of an individual's maximum cognitive capacity, only linear increases in oxygenated hemoglobin were observed in left lateral prefrontal cortex, premotor cortex and supplementary motor area (Yamauchi et al., 2013). Similarly, in a dual-working memory training study, memory load was adapted to one group's skill acquisition. In the adapted group a positive quadratic relationship was observed between memory load and total hemoglobin in PFC. However, a different group of participants that had their memory load yoked to the adapted group showed a negative quadratic relationship between memory load and total hemoglobin (McKendrick et al., 2014). These findings suggest that the presence of a negative quadratic slope during workload measurement is indicative of cognitive overload.

Workload transitions are prevalent in the majority of real world tasks. However, workload transitions are poorly understood. Partially due to a lack of basic discreet manipulations, a lack of objective measures, and poor control of cognitive load states. Working memory tasks will allow for an instantaneous and discrete manipulation of cognitive load. Measurement of prefrontal hemodynamics with fNIRS allows for objective measurement of mental resources required to cope with different levels of task demands. Measurement of individual hemodynamic responses to a range of task demands will allow for individualized workload transitions. Measurement of hemodynamics after workload transitions will test the costs of workload transitions on mental resources beyond those imposed by task demands.

STUDY ONE: PURPOSE

The purpose of study 1 is three fold. The first aim is to develop functions which quantify the effects of spatial working memory load on subjective mental workload, performance, and oxygenated (HbO) and deoxygenated hemoglobin (HbR). These functions can be used on future work in testing the effects of workload transitions. The second aim of the study is to identify stationary points where the relationship between HbO/HbR and spatial memory load deviates from linearity. Previous work has shown that hemodynamics deviate from linearity when a task becomes mentally overloading. The final aim is to determine if an underload state of working memory produces a similar deviation from linearity in HbO and HbR.

METHODS

Participants

13 George Mason university students, aged between 18 and 35 years, with normal or corrected to normal vision participated in the study. Participants had no history of neurocognitive disorders. Participants reported not taking any substance which affects the central nervous system, such as caffeine, nicotine, alcohol and other stimulants and depressants within three hours of the study.

Spatial Memory Task

Each trial began with a black screen presented for 8 secs, followed by a white fixation cross presented for 1 sec. After which the stimuli were presented, specifically as randomly spaced black circles over a gray background (circles could not be less than 150 pixels apart). The circles were presented simultaneously and for a duration of 1 sec. Following stimulus presentation, a random noise mask was displayed for 4 secs. After which a crosshair was displayed and participants were required to report where the stimuli had been and how many there were via a computer mouse click to those locations on the computer screen. Accuracy was defined as the number of circles reported correctly and in the correct location. Inputting more circles than initially presented was penalized. Specifically, if a participant was presented with five circles and input six circles, the number of presented circles was divided by the number of inputted circles, the quotient was then multiplied by the number of circles correctly reported.

NASA TLX

The NASA Task Load Index uses six dimensions to assess mental workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. A score from 0 to 100 is obtained on each scale. Analysis were performed on the scale for mental demand. This scale requires the participant to rate the level of mental and perceptual activity required of the task.

Procedure

Upon entering the laboratory participants completed a demographic survey, after which they were fitted with the fNIRS imaging device. Setup of the fNIRS imaging device took approximately 15-20 minutes. Next participants performed two practice blocks of 10 trials of the spatial memory task. The first block presented each possible spatial load level with load levels varied randomly across trials. The second block presented a spatial load of three on each trial to accommodate the participant to the design of the experimental blocks. The practice blocks were followed by 10 blocks with 10 trials per block of the spatial memory task. The initial load was six objects, and load was altered varied for each following block. The lowest load a participant saw was one, and the highest was ten. Load order across blocks was set up to minimize correlations with linear and exponential trends. After completing a spatial memory block participants were asked to report that blocks’ workload via NASA TLX. Finally, participants took a one minute rest between spatial memory blocks, this included the time it took to complete the NASA TLX. During the rest they were asked to close their eyes and relax for the one minute duration. Total time for the experiment was approximately 60 min.

NIRS Data Acquisition and Processing

Raw light intensities were acquired through a fNIRS Devices fNIR 1000 system composed of 4 emitters and 8 detectors placed over the scalp to provide imaging of frontal cortical regions. 685nm and 830nm wavelengths were used, average emitter to detector distance was 3cm. Raw light intensities were low pass filtered (Ayaz et al., 2011) to remove heart rate, blood pressure, and respiration artifacts. Data was then further filtered with a sliding window filter (Ayaz et al., 2010) to remove potential motion artifacts. Relative chromophore concentrations were calculated by submitting the filtered light intensities to the modified Beer-Lambert law (Ayaz et al., 2012).

Analysis

For each dependent measure a linear mixed effects regression was fitted with Bayesian Information Criterion (BIC) to maximize parsimony of random and fixed effects. Fixed effects included linear, quadratic and cubic effects of memory load. Potential models allowed for intercept, linear slope, quadratic slope and cubic slopes to vary randomly across individuals. Significant fixed effects pertaining to oxygenated and deoxygenated hemoglobin were submitted to a false discovery correction procedure to control for multiple comparisons.

RESULTS

Correct Objects

The most parsimonious linear mixed effects model among those tested with BIC specified a polynomial quadratic fixed effect of working memory load and a random effect of only the quadratic slope (intercept and linear slope were not parsimonious random effects). The random effect, as expected, implies that individuals differed in terms of the maximum number of objects they could report. However, after accounting for this individual variance there was still a parsimonious fixed effect of working memory load. The fixed effects estimates are reported in table 1, from the fixed effects function it was calculated that maximal performance corresponded with the report of 5.1 objects, and this asymptote occurred at a working memory load of 8.9 objects. These values represent estimates of working memory capacity (5.1) (WMC) and the overload boundary (8.9) (OLE). The fixed effect slope is plotted over mean correct objects across WM load in figure 1.

Table 1.

Correct Objects Model Selection (Top 3)

Fixed Effs.	Random Effs.	BIC (dBIC)
WM Load + WM Load^2	WM Load^2	4430.704 (0.00)
WM Load + WM Load^2	Intercept + WM Load + WM Load^2	4460.832 (30.128)
Intercept	Intercept + WM Load + WM Load^2	4492.909 (62.205)

Table 2.

Number of Correctly Reported Objects with Increasing Working Memory Load

	Number of Correct Objects	
	B	*CI*
Fixed		
Intercept	-1.90E-01	-4.50E-01 to 6.00E-02
WM Load	1.23 ***	1.12 to 1.34
WM Load^2	-7.00E-02 ***	-8.00E-02 to -6.00E-02
	Var	*Std. Dev*
Random		
WM Load^2	2.16E-04	1.47E-02
Residual	1.67	1.29
N	13	
Observations	1300	
Notes * p<.05 ** p<.01 *** p<.001		

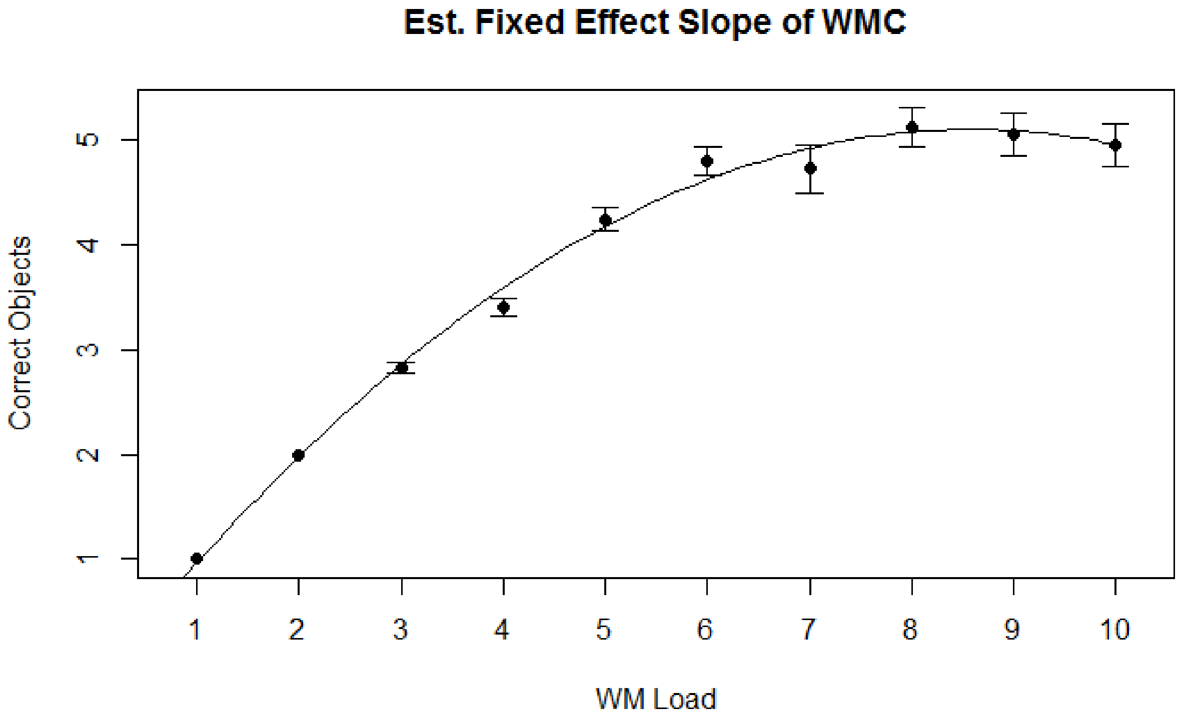

Figure 1. Number of correctly reported objects as a function of working memory load.

The fixed effect quadratic relationship is commensurate with the trend expected from a limited capacity relationship. Initial increases in performance are observed as load increases and is below the capacity limit, and as the capacity limit is reached performance asymptotes. Surprisingly, performance at loads four and five, both of which are at or below the function estimated capacity limit ‘underperform’. Specifically, when 4 objects are presented about 3.5 are reported, and when 5 objects are presented 4 are reported. Similarly, the performance asymptote begins at a working memory load of 6. This trend suggests that information being maintained in working memory begins to degrade above three objects, however, in spite of this working memory capacity is not limited to three objects. Instead, most likely through compensatory executive processing, capacity can be extended beyond where degradation begins up to about five objects. Furthermore, five objects was the population estimate, individuals varied in terms of their capacity limit, random estimates from this measure indicate some participants had a capacity as low as 3.6, while others had a capacity as high as 7.5.

Correct Trials

The most parsimonious generalized linear mixed effects model among those tested with BIC specified working memory load as a fixed effect and participant intercept as a random effect. Similar to the random effects observed for number of correct objects reported, in this model random intercepts imply individual differences in working memory capacity. Specifically, in a logistic model, the intercept or point of subjective equality (PSE) is the value at which participants have a 50% probability of making no errors. This is often used to reflect ability (Hambleton, Swaminathan & Rogers, 1991), and on this task can be used as an estimate of working memory capacity. Furthermore, the absence of random slopes suggests that an individual's theoretical cognitive load range did not vary. The steepness of the slope relates to the range of cognitive load as steeper slopes result in a narrower range and a less steep slope results in a broader range. Since the steepness of slopes did not vary randomly with individuals neither did their cognitive load range. Since slope steepness and cognitive load range did not vary there can be no relationship between an individual's cognitive load range and their PSE, an estimate of their working memory capacity. The fixed effects are the generalizable estimates of working memory capacity and the rate of transition from strong performance to poor performance. The fixed effects estimates are reported in table 2. The fixed estimates of 75, 50, and 25 percent probabilities of success occurred at loads of 4.4, 5.6, and 6.8 respectively. The fixed effect slope is plotted over mean correct trials across WM load in figure 2.

Table 3.

Correct Trials Model Selection (Top 3)

Fixed Effs.	Random Effs.	BIC (dBIC)
WM Load	Intercept	874.178 (0.00)
WM Load	Intercept + WM Load	881.888 (7.170)
WM Load	WM Load	884.942 (10.224)

Table 4.

Log-Odds of Perfect Performance With Increasing Working Memory Load

	Correct Trials	
	Log-Odds	*CI*
Fixed		
PSE	5.62 ***	4.82 to 6.42
WM Load	-9.20E-01 ***	-1.02 to -8.20E-01
	Var	*Std. Dev*
Random		
Intercept	9.72E-01	9.86E-01
N	13	
Observations	1300	
Notes * p<.05 ** p<.01 *** p<.001		

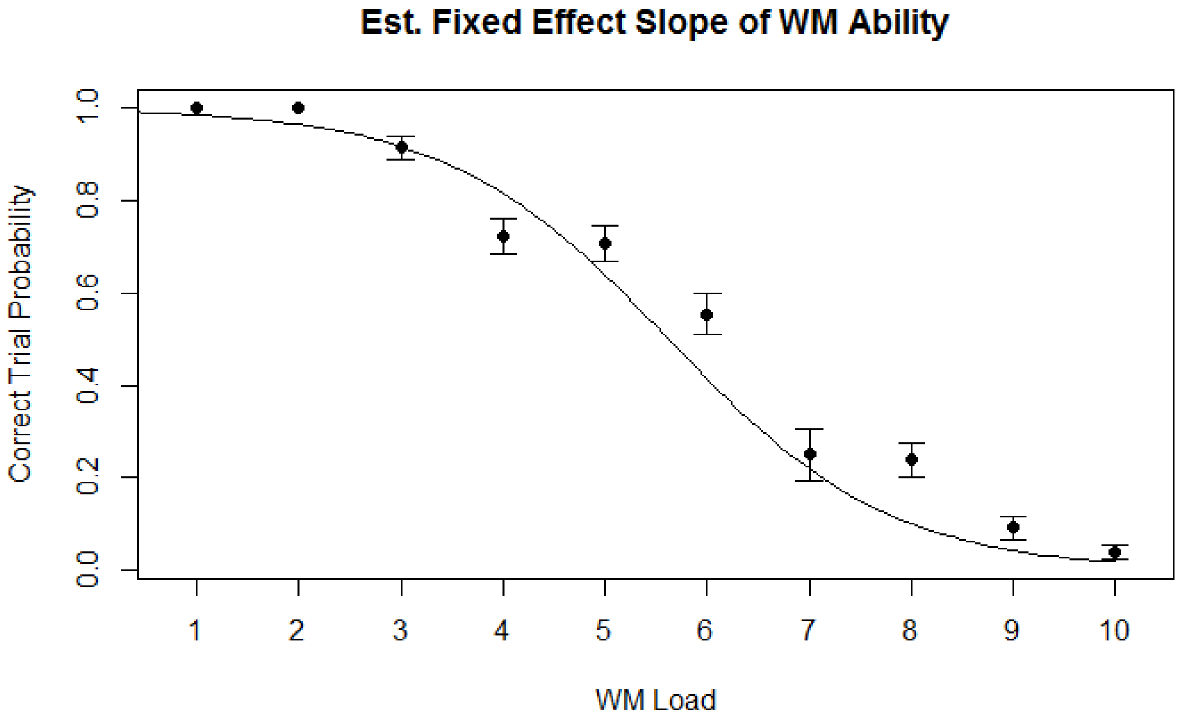

Figure 2. Probability of reporting all presented objects as a function of working memory load.

The logistic model is as expected with error free trials reducing in frequency with increasing memory load. Similar to estimates based on the number of correct objects reported, PSE is estimated at 5.6 for the logistic model of error free trials, or half an object higher than the WMC estimate. While *prima facie* the previous estimates from the object model should be more precise, this model provides estimates of workload range that the other model could not. Specifically, the 75% and 25% estimates, 4.4 and 6.8 respectively. While 75% and 25% estimates are arbitrary they may prove explanatory as potential stationary points when examining hemodynamic models of mental workload. Finally, as in the previous model, error free trial estimates of working memory capacity and workload range varied across participants, some being as low as 3.7 with a workload range of 2.5 to 4.9, and others being as high as 7.1 with a workload range of 5.9 to 8.3

NASA TLX: Mental Demand

The most parsimonious linear mixed effects model among those tested with BIC specified a linear fixed effect of working memory load and random effects of intercept and working memory load. The random effect implies that individuals differed in terms their initial impression of the difficulty of the task and the increase in mental demand as working memory load increased. However, after accounting for this individual variance there was still a parsimonious fixed effect of working memory load. The fixed effects estimates are reported in table 3, and the fixed effect slope is plotted over mental demand across WM load in figure 3.

Table 5.

Mental Demand Model Selection (Top 3)

Fixed Effs.	Random Effs.	BIC (dBIC)
WM Load	Intercept + WM Load	1333.478 (0.00)
WM Load	WM Load	1340.001 (6.523)
Intercept	Intercept + WM Load	1361.478 (28.271)

Table 6.

Perceived Mental Demand as a Function of Working Memory Load

	Mental Demand	
	B	*CI*
Fixed		
Intercept	5.18	-0.76 to 11.12
WM Load	7.37 ***	6.45 to 8.30
	Var	*Std. Dev*
Random		
Intercept	96.01	9.799
WM Load	2.3	1.52
N	13	
Observations	130	
Notes * p<.05 ** p<.01 *** p<.001		

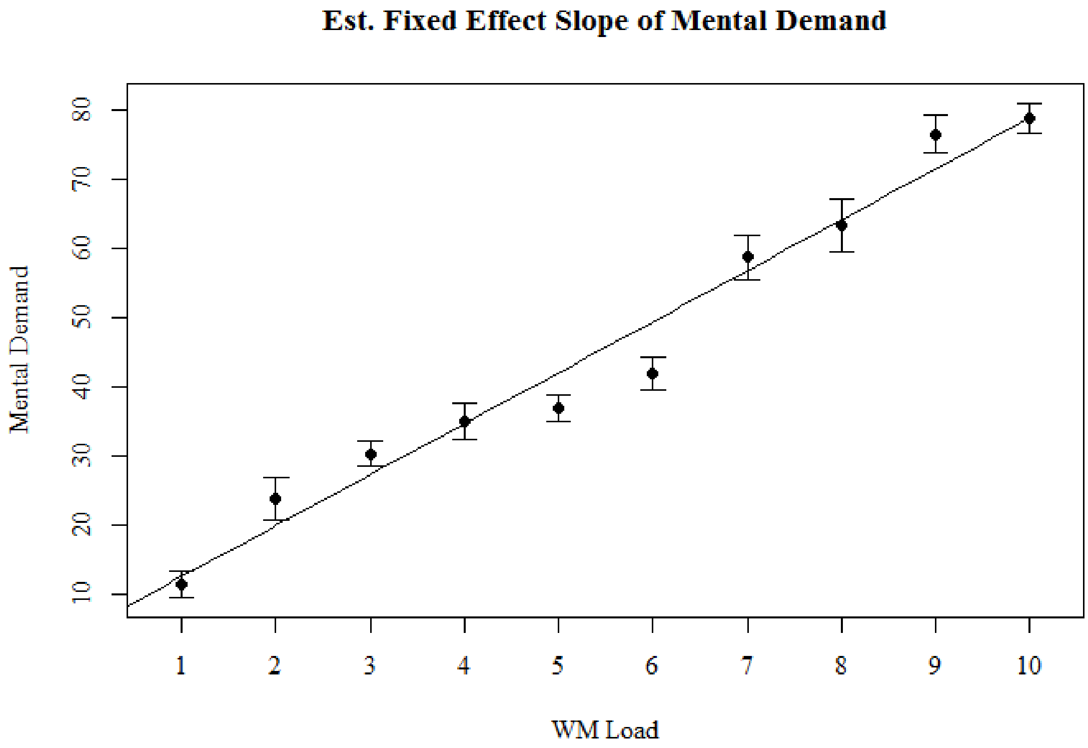

Figure 3. NASA TLX mental demand as a function of working memory load.

As anticipated, mental demand was perceived by participants as increasing linearly with working memory load. This supports the conclusion that the increases in task demand both objectively and subjectively increased mental demand.

Prefrontal Hemodynamics

Hemodynamic response scores were calculated for each trial. Following post-processing of the NIRS signal, group average temporal windows for the hemodynamic response were determined by averaging trial time series across participants and working memory load. Visual inspection of the average trial time series revealed that the peak concentrations of HbO were observed between six and fourteen seconds post stimulus presentation. We selected a temporal window between six and ten seconds post stimulus to represent the peak of the hemodynamic response. The time period from ten to fourteen seconds post stimulus was not used as it was believed that this period was representative of responding to the stimulus. Hemodynamic response scores were submitted to linear mixed effects regression on a trial by trial basis for each participant. Analyses were performed on eight optical channels and the channels are labeled hereafter for their approximate anatomical locations based on where they were placed.

Six optical channels had significant parsimonious effects of working memory load. These effects were primarily located ventrally. The analyses for HbO and HbR in each of the six optical channels are presented in table 4. The model for each optical channel and chromophore was selected independently using BIC measures of parsimony.

Table 7.

Effects of Working Memory Load on Relative Concentrations of HbO and HbR in Frontal Cortex

	Left Dorsolateral Prefrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	4.61E-02	-1.40E-01 to 2.32E-01	6.46E-03	-1.99E-01 to 2.12E-01
WM Load	-3.17E-02 ***	-4.651E-02 to -1.696E-02	-5.37E-02	-1.59E-01 to 5.15E-02
WM Load^2			2.70E-04	-2.48E-02 to 2.54E-02
WM Load^3			4.40E-04	-1.41E-03 to 2.30E-03
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	3.94E-01	6.28E-01	7.86E-02	2.80E-01
Block	6.26E-03	7.91E-02		
WM Load^2			4.93E-04	2.22E-02
WM Load^3			5.67E-06	2.38E-03
Residual	5.48E-01	7.40E-01	1.52E-01	3.89E-01
N	13		13	
Observations	1148		1148	

	Left Ventrolateral Prefrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	1.6341E-01	-2.98E-01 to 6.25E-01	-1.02E-01	-2.98E-01 to 9.39E-01
WM Load			1.23E-01	-3.43E-03 to 2.4954E-01
WM Load^2	-2.44E-03 **	-3.81E-03 to -1.06E-03	-3.73E-02 **	-6.37E-02 to -1.08E-02
WM Load^3			2.61E-03 **	1.01E-03 to 4.20E-03
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				

Intercept	6.88E-01	8.29E-01	3.61E-02	1.90E-01
Block	8.12E-03	9.01E-02		
WM Load^2			8.52E-06	2.92E-03
Residual	5.93E-01	7.70E-01	2.22E-01	4.71E-01
N	13		13	
Observations	1152		1152	
	Left Dorsomedial Prefrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	-3.86E-02	-2.18E-01 to 1.41E-01	-9.70E-02	-2.23E-01 to 2.86E-02
WM Load^2	-2.83E-03 ***	-4.04E-03 to -1.61E-03		
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	7.23E-01	8.50E-01	2.43E-01	4.93E-01
Block	1.12E-02	1.06E-01	3.04E-03	5.51E-02
Residual	4.66E-01	6.82E-01	1.98E-01	4.45E-01
N	13		13	
Observations	1153		1153	
	Left Lateral Orbitofrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	-1.98E-01	-6.44E-01 to 2.48E-01	-1.40E-01	-3.58E-01 to 7.69E-02
WM Load	4.27E-01 **	1.42E-01 to 7.12E-01	6.62E-02	-6.92E-02 to 2.02E-01
WM Load^2	-1.16E-01 ***	-1.69E-01 to -6.24E-02	-3.17E-02	-6.05E-02 to -2.95E-03
WM Load^3	7.68E-03 ***	4.53E-03 to 1.08E-02	2.74E-03 **	9.80E-04 to 4.49E-03
	Var	*Std. Dev*	*Var*	*Std. Dev*

Random				
Intercept	3.35E-01	5.79E-01	5.38E-02	2.32E-01
WM Load	7.79E-02	2.79E-01		
WM Load^2	7.21E-04	2.69E-02	3.17E-05	5.63E-03
Residual	7.16E-01	8.46E-01	2.26E-01	4.75E-01
N	13		13	
Observations	1023		1020	
	Right Lateral Orbitofrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	1.79E-01	-4.00E-02 to 3.97E-01	5.44E-02	-1.41E-01 to 2.50E-01
WM Load			-1.21E-01 ***	-1.79E-01 to -6.34E-02
WM Load^2			9.83E-03 **	3.22E-03 to 1.65E-02
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept			7.04E-02	2.65E-01
WM Load	3.01E-01	5.49E-01		
WM Load^2	3.65E-03	6.04E-02	5.71E-05	7.56E-03
Residual	1.42E+00	1.19E+00	3.92E-01	6.26E-01
N	13		13	
Observations	1124		1121	
	Right Ventrolateral Prefrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	7.47E-01 **	3.22E-01 to 1.171378	-4.53E-02	-2.13E-01 to 1.23E-01
WM Load	-5.39E-01 **	-8.73E-01 to -2.04E-01	8.76E-02	-1.95E-01 to 3.70E-01
WM Load^2	1.04E-01 **	4.11E-02 to 1.67E-01	-2.75E-02	-9.49E-02 to 3.98E-02

WM Load^3	-5.93E-03 **	-9.49E-03 to -2.37E-03	1.94E-03	-2.48E-03 to 6.35E-03
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	1.73E-01	4.15E-01		
WM Load	1.18E-01	3.44E-01	2.14E-01	1.13E-01
WM Load^2	1.75E-03	4.19E-02	1.28E-02	1.13E-01
WM Load^3			5.64E-05	7.51E-03
Residual	9.97E-01	9.98E-01	2.16E-01	4.65E-01
N	13		13	
Observations	1071		1071	

Notes * p<.05 ** p<.01 *** p<.001

Table 8.

HbO LLOFC Model Selection (Top 3)

Fixed Effs.	Random Effs.	BIC (dBIC)
WM Load + WM Load^2 + WM Load^3	Intercept + WM Load + WM Load^2	2712.460 (0.00)
WM Load + WM Load^2 + WM Load^3	Intercept + WM Load + WM Load^3	2716.811 (4.351)
Intercept	Intercept + WM Load + WM Load^2	2718.727 (6.267)

Table 9.

HbO RVLPFC Model Selection (Top 3)

Fixed Effs.	Random Effs.	BIC (dBIC)
WM Load + WM Load^2 + WM Load^3	Intercept + WM Load + WM Load^2	3183.821 (0.00)
WM Load + WM Load^2 + WM Load^3	WM Load + WM Load^2	3184.892 (1.071)
WM Load + WM Load^2	Intercept + WM Load + WM Load^2	3187.420 (3.599)

The optical channels located approximately over left lateral orbitofrontal cortex (LLOFC) and right ventrolateral prefrontal cortex (RVLPFC) produced the most robust nonlinear cerebral hemodynamics as an effect of working memory load (fig. 4 & 5). The effects of working memory load in LLOFC and RVPFC were cubic. In LLOFC increased working memory load initially increased regional activity, after two to three objects activity decreases, reaching an asymptote at seven to eight objects and increasing again hereafter. There was also meaningful individual variance in the rate of initial increase (in HbO only) and the following decrease in activity (in HbO & HbR). In RVPFC the effect of working memory load on HbO and HbR was different. In RVPFC increased working memory load initially decreased regional activity, after three to four objects activity increases, reaching an asymptote at seven to eight objects and decreasing again hereafter. There was meaningful individual variance in the rate of initial decrease (in HbO and HbR), the following increase in activity (in HbO & HbR) and in the final increase (in HbR only). Of note, in RVPFC the fixed effects of working memory load on HbR are not significant unlike in LLOFC.

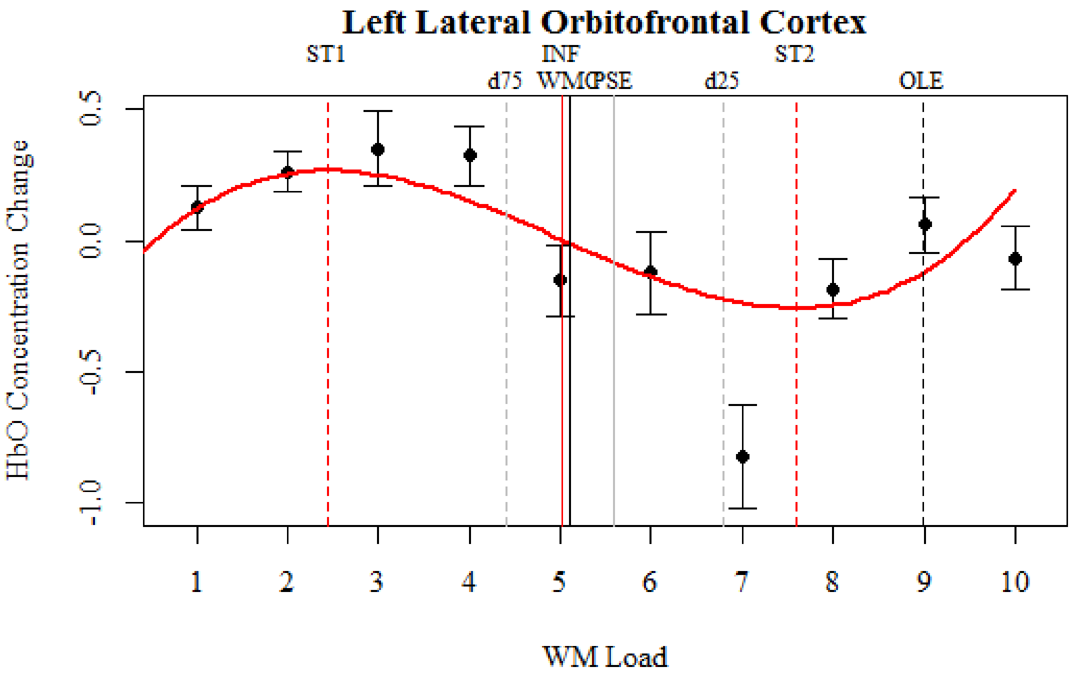

Figure 4. Relative concentration changes in oxygenated hemoglobin (HbO) as a function of working memory load. Annotated from the behavioral models are the estimates of working memory capacity (WMC & PSE) as well as bounding estimates of optimal workload (d_{75} to d_{25}). HbO estimates of working memory capacity (INF) and bounding estimates of optimal load are also annotated (ST1, ST2)

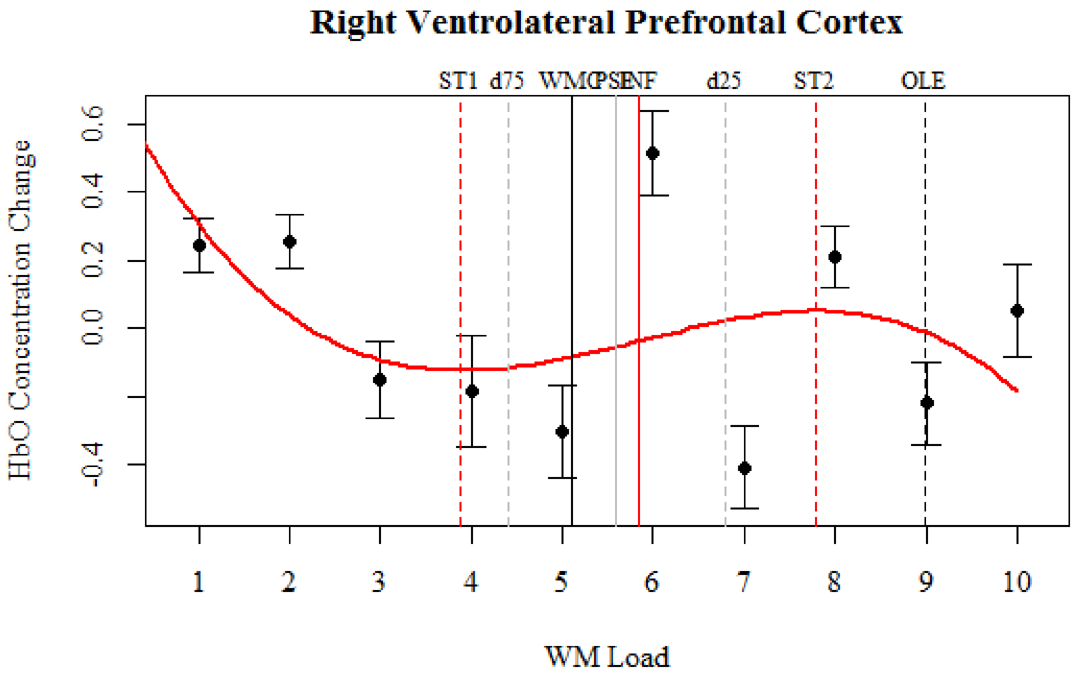

Figure 5. Relative concentration changes in oxygenated hemoglobin (HbO) as a function of working memory load. Annotated from the behavioral models are the estimates of working memory capacity (WMC & PSE) as well as bounding estimates of optimal workload (d_{75} to d_{25}). HbO estimates of working memory capacity (INF) and bounding estimates of optimal load are also annotated (ST1, ST2)

DISCUSSION

The current study aimed to find objective markers to identify different states of cognitive load. The states of interest were underload, optimal load, and overload. To this the effects of working memory load on behavioral performance, subjective perception of workload, and lateral prefrontal hemodynamics were examined. An extended range of working memory loads were used in an attempt to elicit the mental states of interest and nonlinear relationships were the focus of the analyses to provide an objective means of classifying different cognitive load states.

Analyses of behavioral performance revealed different working memory load levels which could inform the identification of different cognitive load states. As working memory load increased the number of spatial objects correctly reported increased quadraticly. The nonlinear relationship reached a stationary point at an approximate load of eight objects, with approximately five objects being reported correctly. This suggests that five objects represent working memory capacity (WMC), and eight objects represent the upper bounds of cognitive load before beginning to transition into overload (OLE). Similar results were found in the logistic analysis of perfect trial performance. This analysis revealed that the 75% probability of a flawless trial occurred at 4.4 objects. The PSE or 50% probability occurred at 5.6 objects, and the 25% probability occurred at 6.8 objects. A classical test theory interpretation of the analysis suggests that 5.6 objects represents the ability to perform the task. This estimate is very close to the estimate of working memory capacity from the other analysis. Furthermore, the range of working memory load between four and seven objects provides another estimate of the boundary regions between underload, optimal load, and overload. With four objects representing the boundary between underload and optimal load, and seven objects representing the boundary between optimal load and overload. It is worth noting that the two analyses estimate different load levels for the boundary between optimal load and overload, however this could be because the selected probability levels in the logistic regression are effectively arbitrary.

Two optical channels located over lateral prefrontal cortex revealed nonlinear hemodynamics as a function of increasing working memory load and can provide a basis for objective cognitive load state classification. The channels over LLOFC and RVPFC showed a cubic relationship with increasing working memory load. The former showed an initial increase in activity, followed by a decrease once working memory load exceeded three objects, and finally increased again as working memory load exceeded seven objects. The latter showed an opposite trend, where activity initially decreased, increased at four objects, and began to decline again after seven objects. These regions nonlinear functions suggest three different cognitive states across the range of working memory load tested. The transitions between the different cognitive states can be assumed to occur at the estimated stationary points, or points with zero slope.

The slope directions observed in LLOFC suggest the measurement of different cognitive states relative to those initially hypothesized. The initial positive slope and transition into a negative slope cohere with previous cognitive neuroscience findings regarding the relationship between working memory and hemodynamics. Namely, hemodynamics have a positive linear relationship with the number of items held in working memory (Braver et al., 1997; Cohen et al., 1997; Culham et al., 2001; Ayaz et al., 2012) up to the prescribed capacity limit of approximately four, and upon exceeding this limit the relationship with hemodynamics becomes negative. Previous findings suggest that the state change occurring as the relationship goes from positive to negative is indicative of overload (Goldberg et al., 1998; Callicott et al., 1999; Durantin et al., 2013). However, our behavioral and hemodynamic evidence suggests otherwise. Specifically, performance is not severely hindered until the second state change, where the relationship between hemodynamics and working memory load is again positive. It is this second state change that most closely resembles the behavioral performance commonly associated with overload. This evidence suggests we were unable to measure an underload state in this channel, and instead measured two states of optimal load and overload. The first cognitive state looks to be caused by loading of working memory capacity. The second state appears to be an interaction between loading working memory capacity, and effort driven compensatory strategies, a recourse to further improve performance in the face of task demands exceeding working memory capacity. This state could be characterized as effort driven optimal load. The final state closely resembles the behavioral performance that would be expected of the measurement of overload. These observations of two states prior to overload introduce new questions regarding the relationship between overload and working memory capacity, suggesting that overload does not occur when working memory capacity is exceeded, but when working memory capacity is exceeded and effort driven compensatory strategies are exhausted.

Unlike in LLOFC, the slope directions observed in RVLPFC do cohere with our initial hypotheses regarding transitions from under to optimal to overload states. At low levels of working memory load hemodynamics have a negative relationship with working memory load, this is what would be expected in an underload state, where excessive cognitive resources are being expended when less are actually needed. In the second cognitive state hemodynamics have a positive relationship with working memory load, the number of reported working memory objects also increases in this state, this increase in performance also coheres with an optimal load state. In the third cognitive state hemodynamics are once again negatively related to working memory load, at the high working memory loads performance began to asymptote and significantly decline. These observations of the third state are what would be expected of an overload state. However, we should be cautious of our interpretation of the initial cognitive state as representing a state of underload. As mentioned when discussing the nonlinear relationship between working memory and LLOFC hemodynamics there were no measureable performance decrements at the lowest load levels. If this were a state of underload, we would expect an occasional error at the lowest memory load due to distraction, yet no such errors occurred.

Different behavioral measurements of working memory capacity cohered with different optical channels over prefrontal cortex. The estimate of working memory capacity from the asymptote of the function representing the number of correctly reported objects for a presented working memory load was very similar to the inflection point of the cubic HbO function of LLOFC. The behavioral estimate was 5.1, and the inflection point of HbO was 5. Similarly, the point of subjective equality (PSE), which represents the memory load that was performed perfectly half the times it was presented, was estimated at 5.6. The PSE was very similar to the inflection point of the cubic HbO function of RVLPFC, which was 5.8. While each hemodynamic estimate coheres more closely with a specific behavioral estimate, overall both the behavioral and hemodynamic estimates are between five and six objects. The similarity between the behavioral and hemodynamic estimates of working memory capacity strengthens the argument that the hemodynamic estimates of cognitive state transitions are useful.

Unlike the estimates of working memory capacity the coherence between hemodynamic and behavioral estimates of cognitive state transitions is less strong. HbO estimates in LLOFC (2.4) of the underload transition are considerably lower than the point of transition estimated based on flawless performance (d75 = 4.4). However, the RVLPFC estimate (3.9) and d75 both place the underload transition boundary around four objects. The behavioral estimates of the overload transition boundary are considerably different. The quadratic model estimates the transition at 8.9 objects and the logistic model estimates the transition at 6.8 objects. Furthermore, both HbO models estimate the transition at 7.6 for LLOFC and 7.8 for RVLPFC, between the two behavioral estimates. Given that the estimates for the logistic model are currently subjective, little weight should be given to them relative to the estimates from the quadratic and HbO models. The logistic estimates could be improved by ‘extending’ their range, instead of using 75 and 25% as the boundaries, 87 and 13% would improve the coherence across the estimates, and should be considered in future studies. However, based on the current models the overload transition estimate relative to estimates of working memory capacity and the underload transition estimate is still the ‘fuzziest’ occurring at a working memory load around to nine objects. Yet in a global sense, given that task demands could only be increased or decreased by one object the coherence between the behavioral and hemodynamic estimates is quite good.

This study aimed’ to model the most parsimonious relationships between perceived mental demand, behavioral performance, and prefrontal hemodynamics as a function of spatial working memory load. An emphasis was placed on finding parsimonious nonlinear relationships in prefrontal HbO and HbR, with the goal of using components of the nonlinear functions to objectively describe different cognitive workload states at the group and individual level. Exploratory modeling was successful, revealing multiple behavioral estimates of working memory capacity and cognitive state boundaries. Most importantly, two nonlinear cubic polynomial relationships were observed in HbO for optical channels over left lateral orbitofrontal cortex and right ventrolateral prefrontal cortex. These functions can be used in future studies of workload transitions as they both have relatively good coherence with behavioral estimates, expand on those estimates, and measured three different states of cognitive load.

STUDY TWO: PURPOSE

The purpose of study two is to test the effects of workload transitions by replicating the effects of spatial memory load on behavioral performance, subjective report and hemodynamics observed in study one, adapting cognitive states to individuals, and testing how transitions to different cognitive states alter behavioral performance, subjective report and prefrontal hemodynamics relative to when cognitive state transitions do not occur. Workload transitions in either increasing or decreasing direction have been shown to consistently hinder performance (Cox-Fuenzalida et al., 2004; Cox-Fuenzalida et al., 2005; Cox-Fuenzalida et al., 2006; Cox-Fuenzalida, 2007). However, load levels in these studies were not adapted to individuals and in some cases the load levels showed no performance differences. Transitions to over and underload have been understudied, even though they are commonly implicated in human error across many complex tasks (Parasuraman, 2008). Study one assumed that changes in prefrontal hemodynamics are representative of cognitive resources required for task completion. Workload transitions are anticipated to additionally tax cognitive resources and hence alter the functional relationship between prefrontal hemodynamics and cognitive load. The subjective, behavioral and hemodynamic functions observed in study one will be used to adapt workload transitions to individuals and systematically test their effects. Specifically, testing the effects of workload transition direction (up or down) and cognitive load state (under or overload) relative to identical cognitive load levels when no transitions has occurred by examining changes in the subjective, behavioral and hemodynamic slope coefficients.

METHODS

Participants

17 George Mason university students, aged between 18 and 45 years, with normal or corrected to normal vision. Participants had no history of neurocognitive disorders. Participants had not taken any substance which affects the central nervous system, such as caffeine, nicotine, alcohol and other stimulants and depressants within three hours of the study.

Spatial Memory Task

Identical to that used in study one.

NASA TLX

Identical to that used in study one.

Procedure: Session One

Identical to that used in study one.

Procedure: Transition selection

Following the first experiment participants took an hour break while the second study was prepared. During the break each participant's subjective, behavioral and hemodynamic data was fit to the function shapes observed in study 1. Individual estimates of underload, low load, high load and overload were made for each participant. The estimates were primarily determined by the stationary points and inflection point observed in each individual’s cubic function for LLOFC HbO. Each stationary point was rounded to the nearest whole numeral, increased and decreased by one, yielding values both greater and less than the value of the stationary point. For extreme cases where participant’s ability was below four, or above seven objects the LLOFC HbO function could only estimate one cognitive load state transition. In these instances, the available estimate was used and either the minimum (1,3) for low ability participants, or maximum (8,10) for high ability cognitive load state transition was used for the state that could not be estimated.

Procedure: Session Two

Upon completion of the break, participants were refitted with the NIRS imaging device. The spatial memory task was used again. Participants performed 10 blocks of workload transitions. Each transition block was composed of 10 trials, 6 trials at an initial load level and 4 trials at the transition level. The 10 blocks were composed of 6 transition conditions and 4 constant conditions based on the four states of cognitive load. The six transition conditions were as follows: underload to low load, low to high load, high to overload, overload to high load, high to low load, and low to underload. The four constant condition blocks represented comparison blocks in which the load level did not transition but was maintained at the initial level for all 10 trials. Load order across blocks was set up to minimize correlations with linear and exponential trends. After completing a spatial memory block participants were asked to report that blocks' workload via NASA TLX. Finally, participants took a one minute rest between spatial memory blocks, this included the time it took to complete the NASA TLX. During the rest they were asked to close their eyes and relax for the one minute duration. Assessment of transition effects lasted for approximately 60 mins.

NIRS Data Acquisition and Processing

NIRS data acquisition and processing were identical to study one.

Analysis: Session One

Analysis of each dependent measure (subjective, behavioral and hemodynamic) were analyzed identical to study one. Significance, beta coefficient values and 95% confidence intervals of effects were compared to assess the validity of the replication of study one's effects in study two. Replication was considered successful if the effect in study two was significant at $p < 0.05$, study two's beta coefficient was within the 95% confidence interval of study one's effect, and study one's beta coefficient was with the 95% confidence intervals of study two's effect.

Analysis: Session Two

Only the last four trials of each experimental block were used in the analysis. Four conditions were created, representing no transitions, transitions, increasing transitions, and decreasing transitions respectively. The no transition condition was composed of the last four trials for each of the blocks lacking a transition, yielding estimates for underload, low load, high load, and underload. The increasing transitions condition was composed of the last four trials of the three blocks in which the transition was an increase in task demands. The decreasing transitions condition was composed of the last four trials of the three blocks in which the transition was a decrease in task demands. The transitions condition was composed of the last four trials of the six blocks where a transition occurred.

For each dependent (subjective, behavioral, and hemodynamic) measure a linear mixed effects regression will be fitted with BIC to maximize parsimony of random and fixed effects. Potential random effects are again intercept, slope and their combination as either correlated or uncorrelated. For each dependent measure, increasing, decreasing and transition conditions are compared to the no transition condition.

When the effect of transitions failed to reject the null hypothesis equivalence tests were performed to assess if there was no difference between workload transitions and no-transitions. The effect of workload transitions was considered equivalent if the difference estimate and both tails of the 95% confidence interval of workload transitions relative to no-transitions was contained within the 95% confidence intervals of the no-transitions effect. If these conditions were not met, the test was classified as inconclusive.

RESULTS: SESSION ONE

Correct Objects

The most parsimonious linear mixed effects model among those tested with BIC specified a polynomial quadratic fixed effect of working memory load and a random effect of only the quadratic slope (intercept and linear slope were not parsimonious random effects). The random effect, as expected, implies that individuals differed in terms of the maximum number of objects they could report. However, after accounting for this individual variance there was still a parsimonious fixed effect of working memory load. The fixed effects estimates are reported in table 5, from the fixed effects function it was calculated that maximal performance corresponded with the report of 5.3 objects, and this asymptote occurred at a working memory load of 9.3 objects. These values represent estimates of working memory capacity (5.3) (WMC) and the overload boundary (9.3) (OLE). The fixed effect slope is plotted over mean correct objects across WM load in figure 6.

Table 10.

Number of Correctly Reported Objects with Increasing Working Memory Load

	Number of Correct Objects	
	B	*CI*
Fixed		
Intercept	-9.75E-02	-4.50E-01 to 6.00E-02
WM Load	1.18 ***	1.08 to 1.28
WM Load^2	-6.48E-02 ***	-7.61E-02 to -5.34E-02
	Var	*Std. Dev*
Random		
WM Load^2	2.25E-04	1.50E-02
Residual	1.82	1.35
N	17	
Observations	1700	
Notes * p<.05 ** p<.01 *** p<.001		

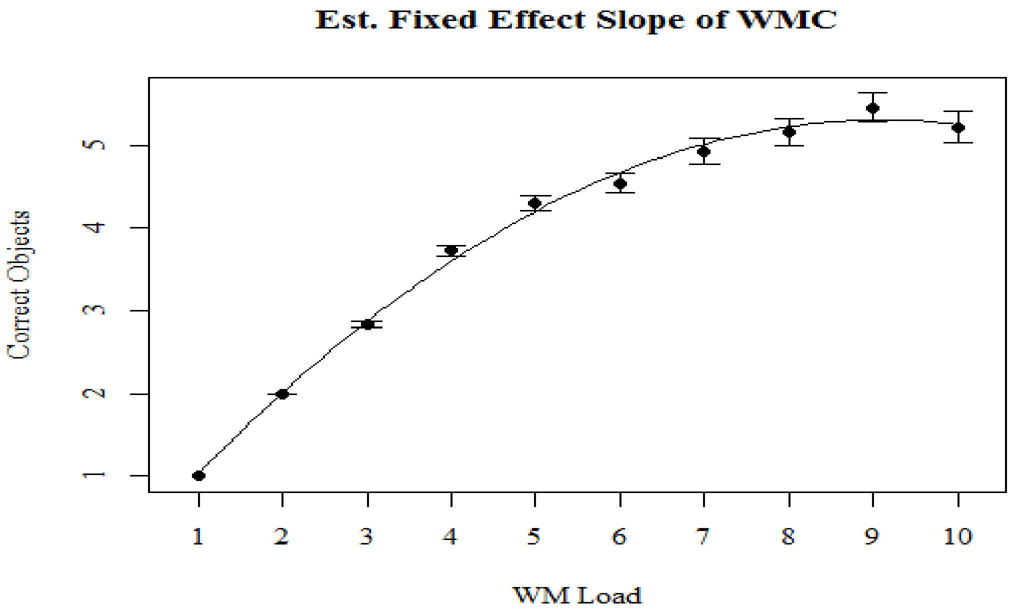

Figure 6. Number of correctly reported objects as a function of working memory load.

Examination of the beta coefficients and confidence intervals of the effects in study one and study two reveal that both the linear and quadratic slopes observed in study one were successfully replicated in study two. The comparisons are depicted in figure 7.

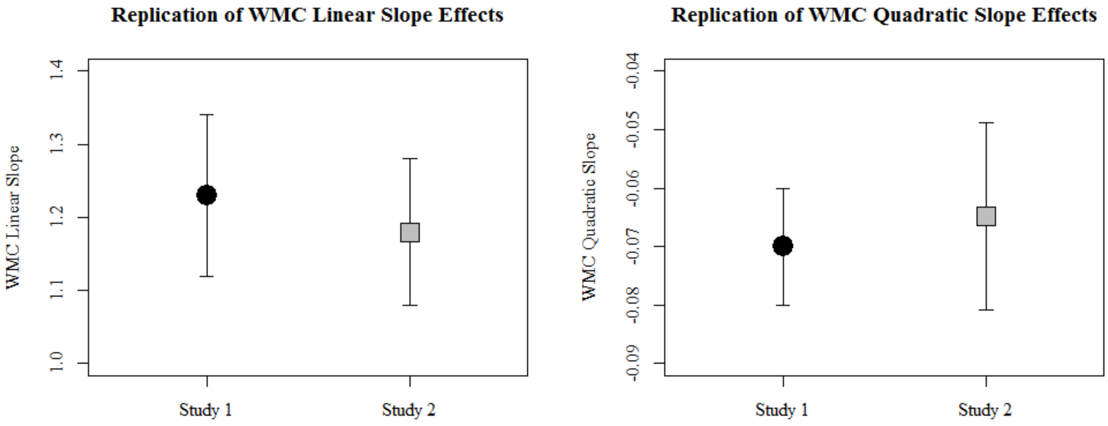

Figure 7. Beta coefficients and 95% confidence intervals of linear and quadratic slopes for correctly reported objects in study one and study two.

Correct Trials

The most parsimonious generalized linear mixed effects model among those tested with BIC specified working memory load as a fixed effect and participant intercept as a random effect. Similar to the random effects observed for number of correct objects reported, in this model random intercepts imply individual differences in working memory capacity. Furthermore, the absence of random slopes suggests that an individual's theoretical workload range did not vary, and consequentially an individual's workload range was not related to their working memory capacity. The fixed effects are the generalizable estimates of working memory capacity and the rate of transition from strong performance to poor performance. The fixed effects estimates are reported in table 6. The fixed estimates of 87, 50, and 13 percent probabilities of success occurred at loads of 3.5, 5.6, and 7.7 respectively. The fixed effect slope is plotted over mean correct trials across WM load in figure 8.

Table 11.

Log-Odds of Perfect Performance With Increasing Working Memory Load

	Correct Trials	
	Log-Odds	*CI*
Fixed		
PSE	5.62 ***	4.91 to 6.33
WM Load	-8.97E-01 ***	-9.80E-01 to -8.14E-01
	Var	*Std. Dev*
Random		
Intercept	9.87E-01	9.94E-01
N	17	
Observations	1700	
Notes * p<.05 ** p<.01 *** p<.001		

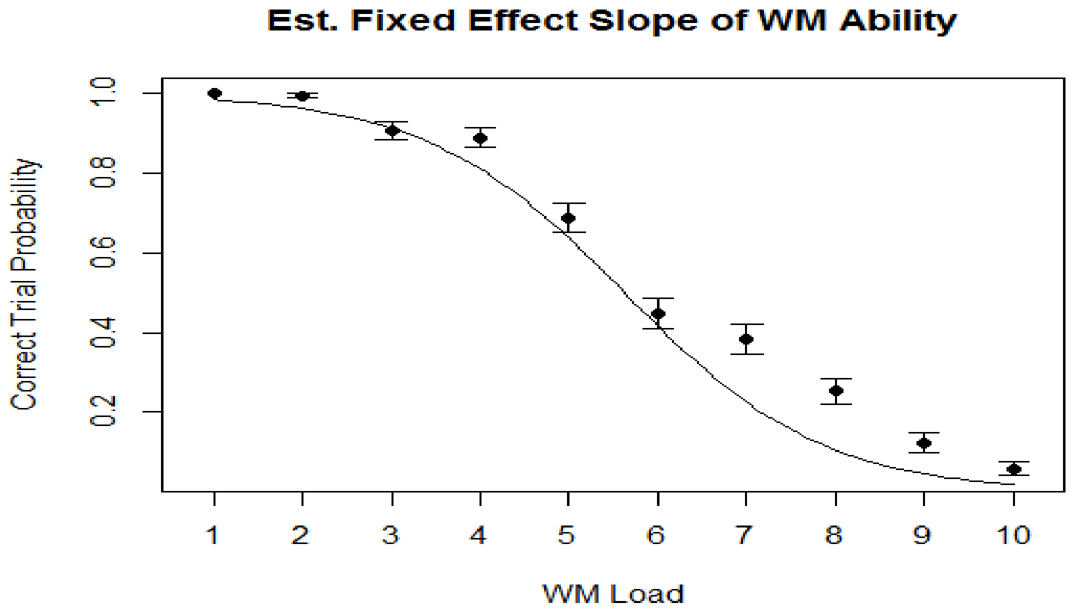

Figure 8. Probability of reporting all presented objects as a function of working memory load.

Examination of the beta coefficients and confidence intervals of the effects in study one and study two reveal that both the PSE and linear slopes observed in study one were successfully replicated in study two. The comparisons are depicted in figure 9.

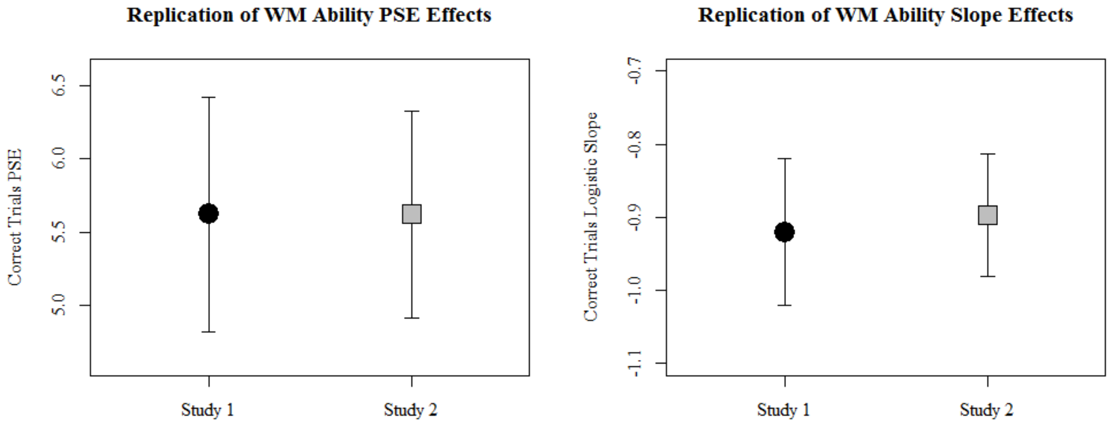

Figure 9. Beta coefficients and 95% confidence intervals of PSE and linear slopes for correct trials in study one and study two.

NASA TLX: Mental Demand

The most parsimonious linear mixed effects model among those tested with BIC specified a linear fixed effect of working memory load and random effects of intercept and working memory load. The random effect implies that individuals differed in terms their initial impression of the difficulty of the task and the increase in mental demand as working memory load increased. However, after accounting for this individual variance there was still a parsimonious fixed effect of working memory load. The fixed effects estimates are reported in table 7, and the fixed effect slope is plotted over mental demand across WM load in figure 10.

Table 12.

Perceived Mental Demand as a Function of Working Memory Load

	Mental Demand	
	B	*CI*
Fixed		
Intercept	8.22	0.57 to 15.86
WM Load	7.15 ***	5.73 to 8.56
	Var	*Std. Dev*
Random		
Intercept	222.25	14.91
WM Load	7.91	2.81
N	17	
Observations	170	
Notes * p<.05 ** p<.01 *** p<.001		

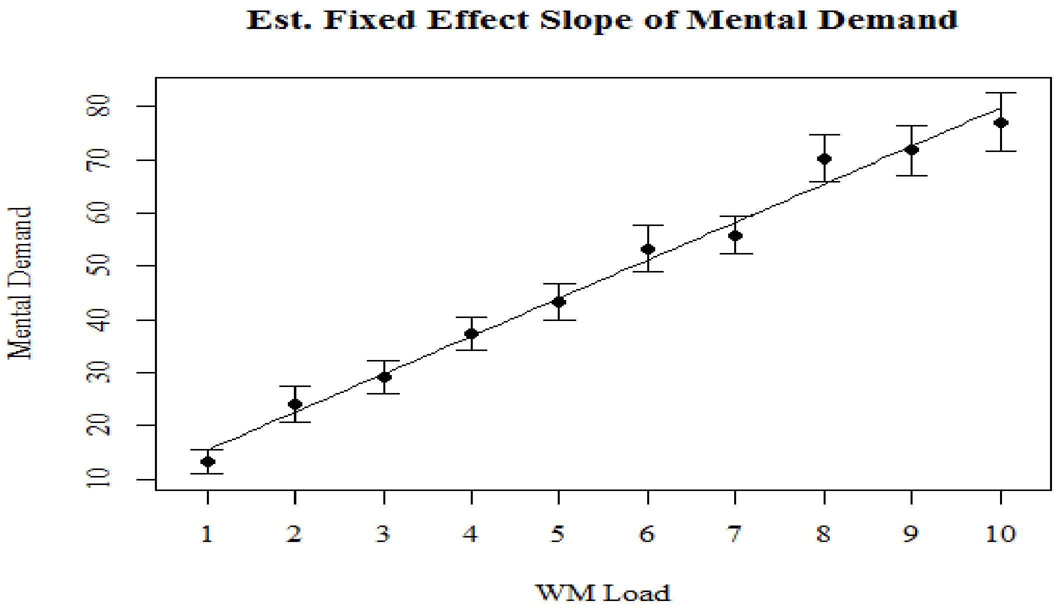

Figure 10. NASA TLX mental demand as a function of working memory load.

Examination of the beta coefficients and confidence intervals of the effect in study one and study two reveal that the linear slope observed in study one was successfully replicated in study two. The comparison is depicted in figure 11.

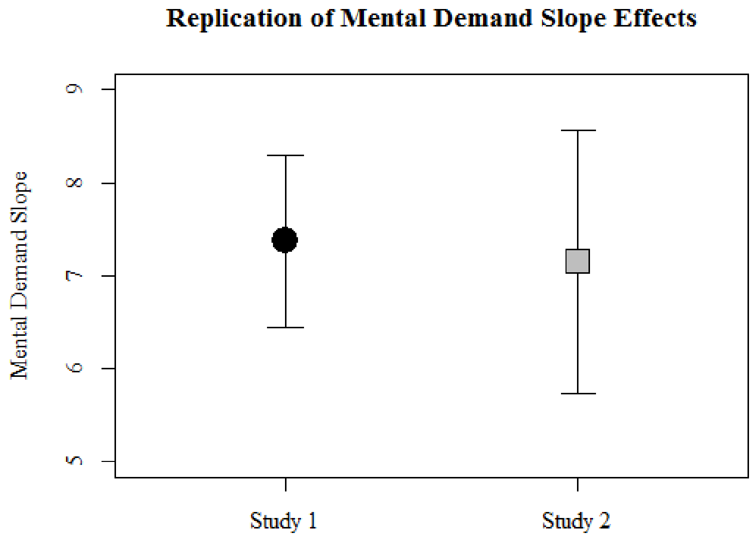

Figure 11. Beta coefficients and 95% confidence intervals linear slopes for NASA TLX: mental demand in study one and study two.

Prefrontal Hemodynamics

Hemodynamic response gain scores were calculated for each trial. Following post-processing of the NIRS signal, group average temporal windows for peak hemodynamic response were determined by averaging trial time series across participants and working memory load. Visual inspection of the average trial time series revealed that the peak concentrations of HbO were observed between six and fourteen seconds post stimulus presentation. We selected a temporal window between six and ten seconds post stimulus to represent the peak of the hemodynamic response. The time period from ten to fourteen seconds post stimulus was not used as it was believed that this period was representative of responding to the stimulus.

Only the optodes which showed cubic polynomial effects from study one were further analyzed. The most parsimonious models for each optode are reported in table 8. The optode over LLOFC was the only one of the two to show a significant cubic polynomial relationship with working memory load. The fixed effect slopes of LLOFC are plotted in figure 12.

Table 13.

Effects of Working Memory Load on Relative Concentrations of HbO and HbR in Frontal Cortex

	Left Lateral Orbitofrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
Intercept	1.28E+00	-4.08E-02 to 2.60E+00	1.50E-01	-5.51E-01 to 8.51E-01
WM Load	4.62E-01 **	1.90E-01 to 7.33E-01	4.25E-01 ***	2.33E-01 to 6.18E-01
WM Load^2	-1.16E-01 ***	-1.71E-01 to -6.06E-02	-9.70E-02 ***	-1.37E-01 to 5.71E-02
WM Load^3	8.17E-03 ***	4.88E-03 to 1.15E-02	6.42E-03 ***	4.04E-03 to 8.79E-03
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	7.16E+00	2.68E+00	1.88E+00	1.37E+00
WM Load	1.00E-02	1.00E-01		
WM Load^2	1.59E-04	1.26E-02	2.96E-05	5.44E-03
Residual	1.44E+00	1.20E+00	7.53E-01	8.68E-01
N	17		17	
Observations	1659		1659	
	Right Ventrolateral Prefrontal Cortex			
	HbO		HbR	

	B	*CI*	*B*	*CI*
Fixed				
Intercept	1.97E+00 **	9.16E-01 to 3.04E+00	1.26E+00 ***	9.80E-01 to 1.53E+00
WM Load	1.99E-01	-9.47E-02 to 4.93E-01	2.53E-01	-3.02E-01 to 8.08E-01
WM Load^2	-5.665E-02	-1.17E-01 to 3.46E-03	-6.71E-02	-1.78E-01 to 4.38E-02
WM Load^3	4.34E-03 *	7.53E-04 to 7.93E-03	4.96E-03	-4.37E-02 to 1.43E-02
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	4.31E+00	2.08E+00		
WM Load	5.47E-03	7.39E-02	1.18E+00	1.08E+00
WM Load^2	3.46E-05	5.88E-03	4.65E-02	2.16E-01
WM Load^3			3.57E-04	1.89E-02
Residual	1.69E+00	1.30E+00	8.45E-01	9.19E-01
N	17		17	
Observations	1636		1636	
Notes * p<.05 ** p<.01 *** p<.001				

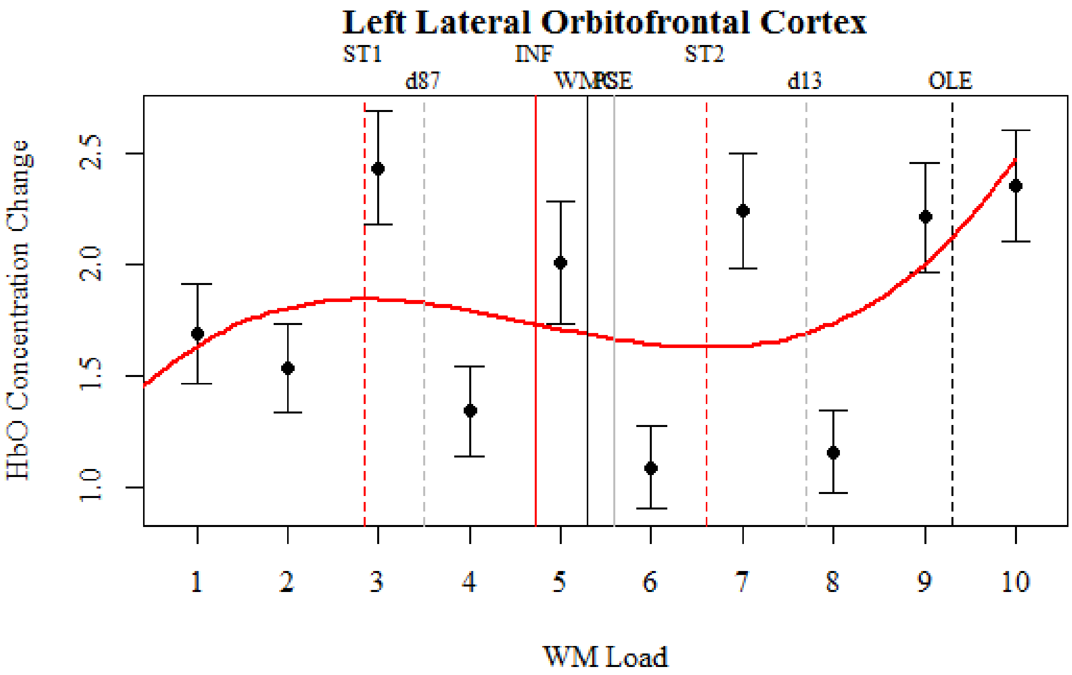

Figure 12. Relative concentration changes in oxygenated hemoglobin (HbO) as a function of working memory load. Annotated from the behavioral models are the estimates of working memory capacity (WMC & PSE) as well as bounding estimates of optimal workload (d_{87} to d_{13}). HbO estimates of working memory capacity (INF) and bounding estimates of optimal load are also annotated (ST1, ST2)

Comparisons of the beta coefficients and confidence intervals of the effects in study one and study two for LLOFC (figure 13), and RVLPFC (figure 14) are plotted below. The effects observed in LLOFC in study two successfully replicated the effects observed in this optode in study one. However, the effects observed in RVLPFC in study one were not replicated in study two. In study two a stronger cubic polynomial relationship was also observed for HbR in LLOFC, this effect was not present in study one.

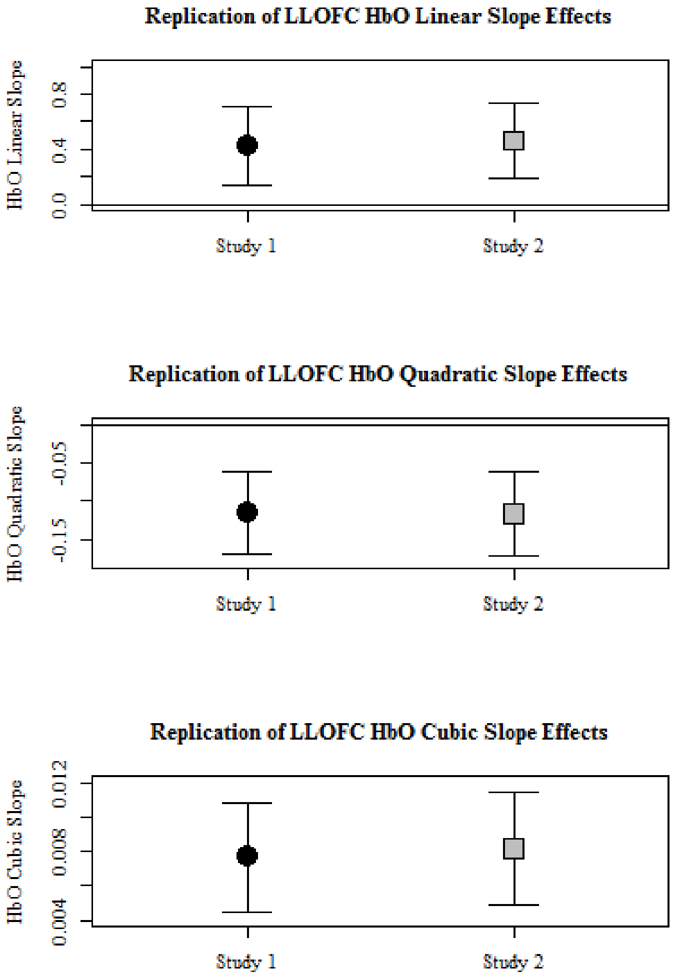

Figure 13. Beta coefficients and 95% confidence intervals of LLOFC HbO linear, quaratic, and cubic slopes in study one and study two.

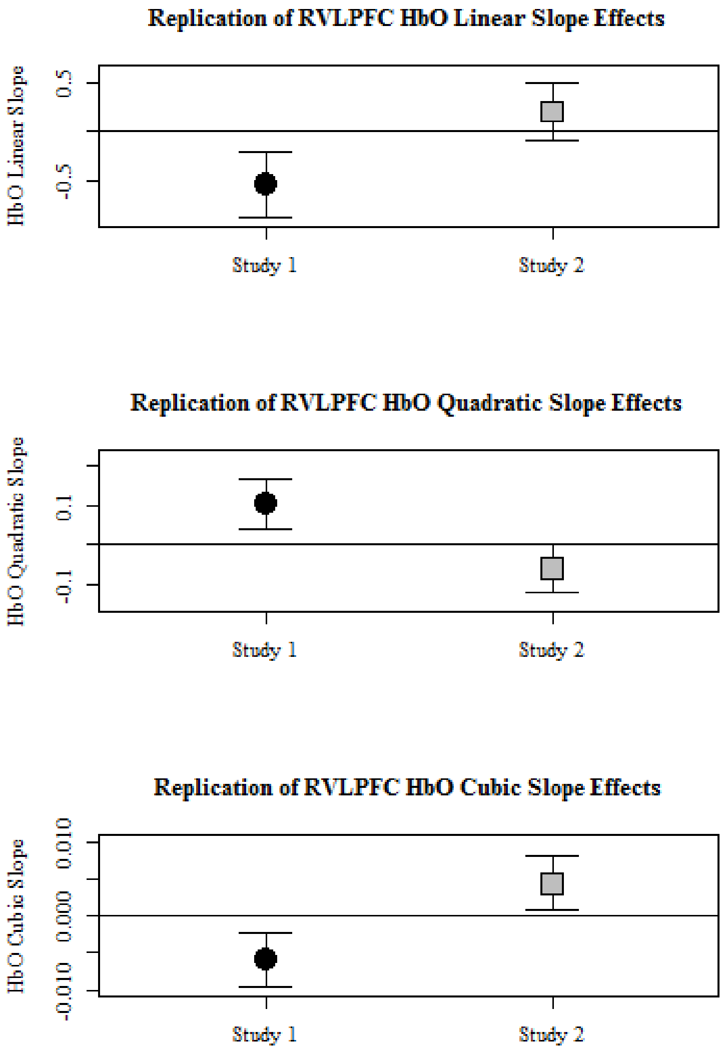

Figure 14. Beta coefficients and 95% confidence intervals of RVLPFC HbO linear, quaratic, and cubic slopes in study one and study two.

DISCUSION: SESSION ONE

The first testing session of study two aimed to replicate the effects observed in study one to provide an empirical foundation from which the effects of workload transitions could be measured. The behavioral and subjective measures from study one were successfully replicated in study two. Hemodynamic effects of HbO were successfully replicated in LLOFC but not in RVLPFC.

The successful replication of the cubic function in LLOFC but not in RVLPFC, informs the ambiguity regarding the types of cognitive load states observed with this paradigm mentioned in the discussion of study one. In study one the difference in slope directions observed between LLOFC and RVLPFC suggested the task load of about 1 to 4 objects represented standard cognitive in LLOFC but underload in RVLPFC. This was because the initial positive slope as observed in LLOFC coheres with previous work on the linear loading of working memory and is inconsistent with inefficient compensatory strategies such as mind wandering, believed to be indicative of underload. As mentioned in the discussion of study one, the initial negative slope observed in RVLPFC was more consistent with the pattern of hemodynamics expected during underload. The successful replication of the LLOFC effects, and inconclusive replication of the RVLPFC effects strengths the case for the interpretation of the workload states represented in the LLOFC effects. Specifically, task loads of 1-3 objects represent standard cognitive load, increasing the task demands to 4-7 objects induces effort driven cognitive load, and further increasing task demands to 8-10 objects induces cognitive overload.

As in study one there were interesting similarities and differences between the behavioral and hemodynamic estimates of the cognitive load state boundaries. All measures of working memory capacity or ability suggested the characteristic to be between 5 and 6 objects, 4.7 for the hemodynamic inflection point, 5.3 for the local maxima of correctly reported objects, and 5.6 for the PSE of correct trials. As in study one the correct objects estimate of overload (OLE), the task demand at which the local maxima occurred 9.3, was significantly higher than the second hemodynamic stationary point 6.6, and the correct trials 13% probability (7.7). The second hemodynamic stationary point and the correct trials 13% probability were between 7 and 8 objects, but their estimates still differed by almost a whole object. Unlike in study one, where the first state transition estimates compared the first hemodynamic stationary point and correct trials 75% probability, study two assumed correct trials 87% probability to be the better comparison. Indeed, the estimates of study two's first hemodynamic stationary point 2.9 and the correct trials 87% probability 3.3 are closer than the comparison made in study one. Both estimates indicate a state transition at around 3 objects. While the probability based comparisons are arbitrary, understanding which probabilities best line up with the hemodynamic estimates may prove useful and implementing this methodology of cognitive load state estimation on tasks other than the working memory task used here.

Overall, replication of the majority of subjective, behavioral and hemodynamic effects of study one in study two provides a foundational basis for analyzing the effects of workload transitions. First, it strengthens the evidence for the nonlinear relationships observed in the hemodynamics of the LLOFC optical channel. Second, it validates the procedure used for session two, where task demands were adaptively selected for each individual’s cognitive load states based predominantly on their hemodynamics in LLOFC. We can now test if the presence of workload transitions increasing and decreasing to specific cognitive load states have effects on the performance, subjective report and hemodynamics of those cognitive load states.

RESULTS: SESSION TWO

Correct Objects

The most parsimonious linear mixed effects model among those tested with BIC specified a polynomial quadratic fixed effect of cognitive load state interacting with workload transitions and random effects of participant intercept and linear slope of cognitive load state. The fixed effects estimates are reported in table 9. The fixed effect slopes of correct objects reported are plotted across cognitive load states in figure 15.

Table 14.

Correct Objects as a Function of Cognitive Load State

	Correct Objects	
	B	*CI*
Fixed		
No-Trans Int	-1.03 *	-1.99 to -0.06
Trans Int	-5.21E-02	-1.24to 1.13
No-Trans Linear Slope	2.99 ***	2.16 to 3.81
No-Trans Quadratic Slope	-3.38E-01 ***	-0.50 to -0.18
Trans Linear Slope	-3.21E-02	-1.08 to 1.02
Trans Quadratic Slope	1.47E-02	-0.19 to 0.22
	Var	*Std. Dev*
Random		
Intercept	7.84E-01	8.86E-01
Cognitive Load State	2.32E-01	4.82E-01
N	17	
Observations	680	

Notes * p<.05 ** p<.01 *** p<.001

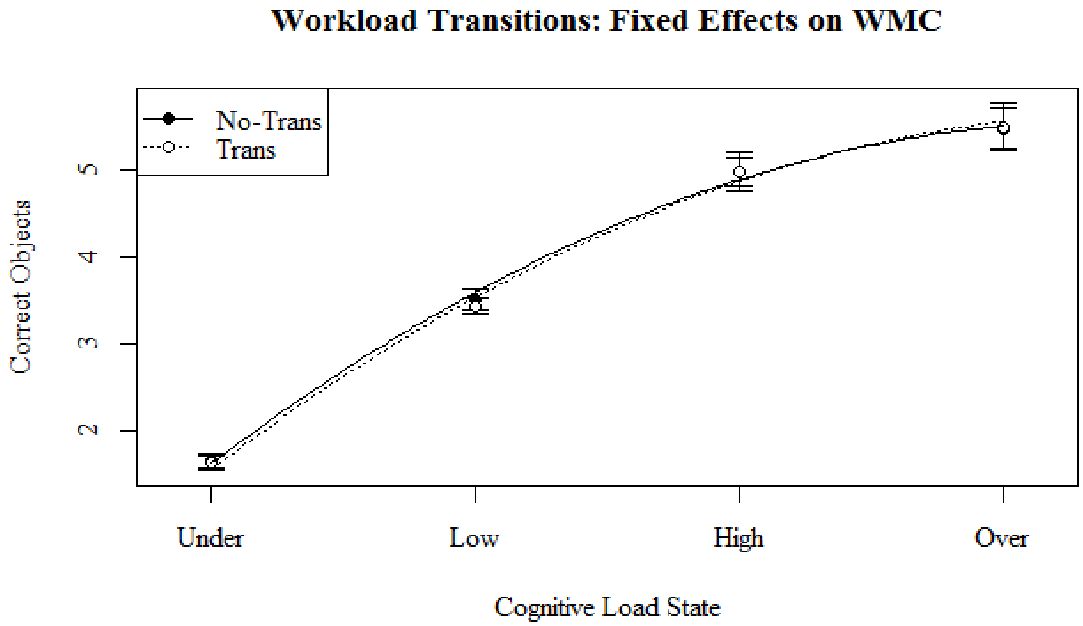

Figure 15. Number of correctly reported objects as a function of cognitive load state and transition condition.

Intercept, linear and quadratic slopes for the workload transitions condition all failed to reject the null hypothesis in comparison to the equivalent effects of the no transition condition. Equivalence comparisons were performed to determine if there is evidence to accept the null hypothesis of no difference between the conditions. The estimates for transition intercept (figure 16) and linear slope (figure 17) and quadratic slope (figure 18) were completely bound within the 95% confidence intervals of their no-transition counterpart effects. However, all the transitions effect confidence intervals were not bounded by the confidence intervals of the no-transitions effect. This suggests there is not no evidence for accepting the null hypothesis of no difference. Instead we would classify the tests as inconclusive.

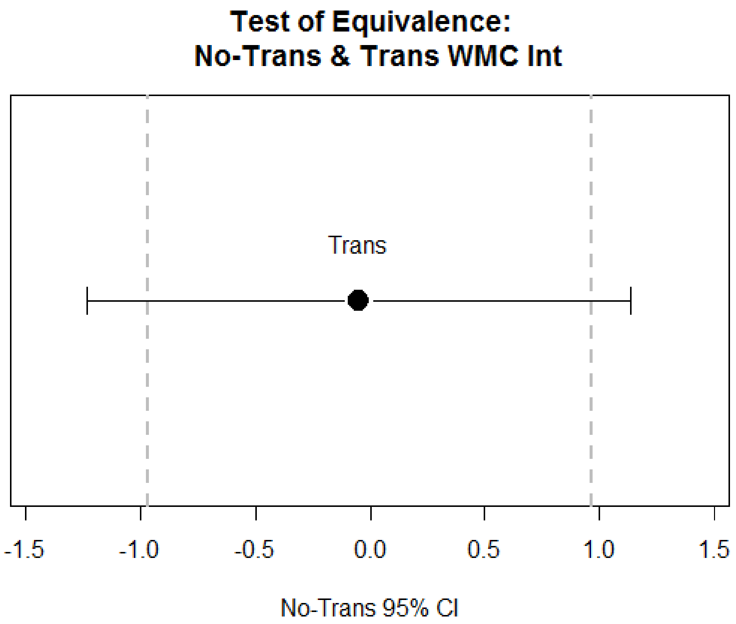

Figure 16. Beta coefficient and 95% confidence interval of difference between intercepts of workload transitions and no-transitions relative to the 95% confidence interval of the no-transition intercept estimate.

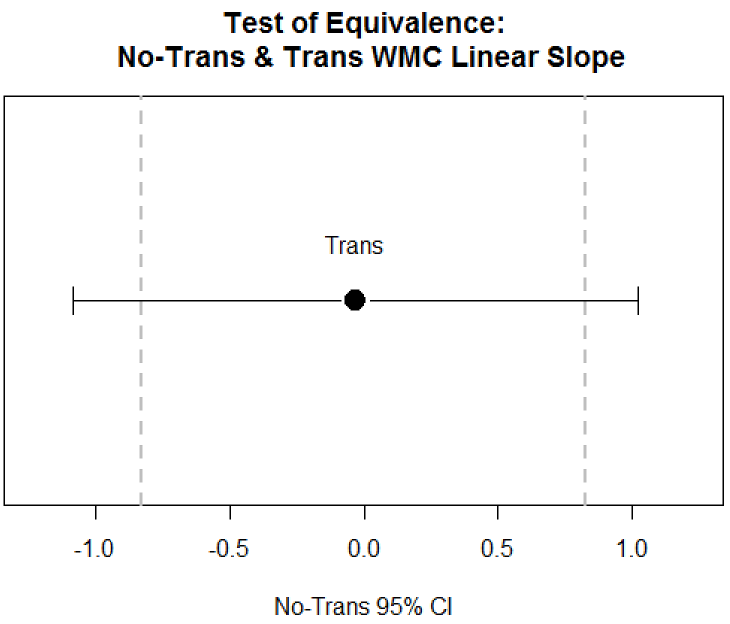

Figure 17. Beta coefficient and 95% confidence interval of difference between linear slope of performance of workload transitions and no-transitions relative to the 95% confidence interval of the no-transition linear slope estimate.

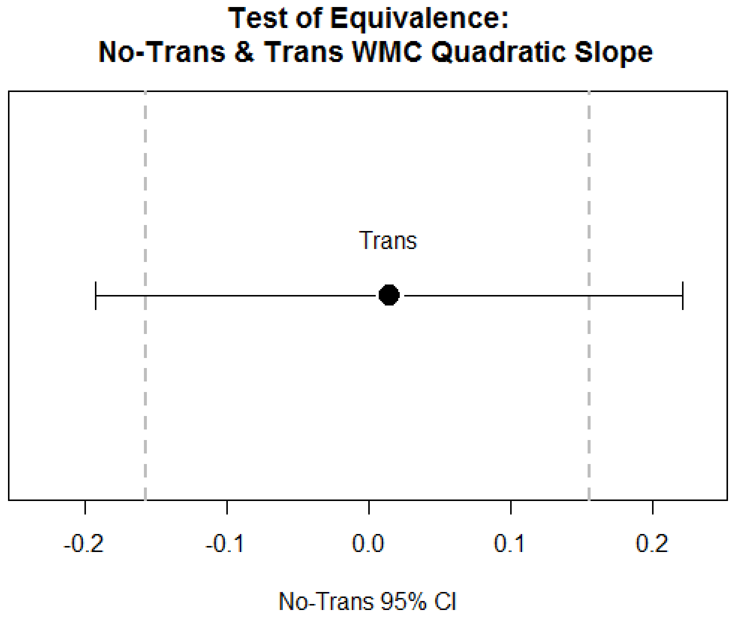

Figure 18. Beta coefficient and 95% confidence interval of difference between quadratic slope of performance of workload transitions and no-transitions relative to the 95% confidence interval of the no-transition quadratic slope estimate.

Correct Trials

The most parsimonious generalized linear mixed effects model among those tested with BIC specified a logistic slope of workload state interacting with workload transitions and the random effect of participant intercept. The fixed effects estimates are reported in table 10. The fixed effect slopes of correct trials are plotted across cognitive load states in figure 19.

Table 15.

Correct Trials as a Function of Cognitive load State

	Correct Trials	
	B	*CI*
Fixed		
No-Trans PSE	2.04E+00 ***	1.78E+00 to 2.24E+00
No-Trans Slope	-2.58E+00 ***	-3.14E+00 to -2.03E+00
Trans PSE	-2.23E-01	-8.78E-01 to 0.34E-01
Trans Slope	5.27E-01	-1.10E-01 to 1.17E+00
	Var	*Std. Dev*
Random		
Intercept	1.26E+00	1.12E+00
N	17	
Observations	680	
Notes * p<.05 ** p<.01 *** p<.001		

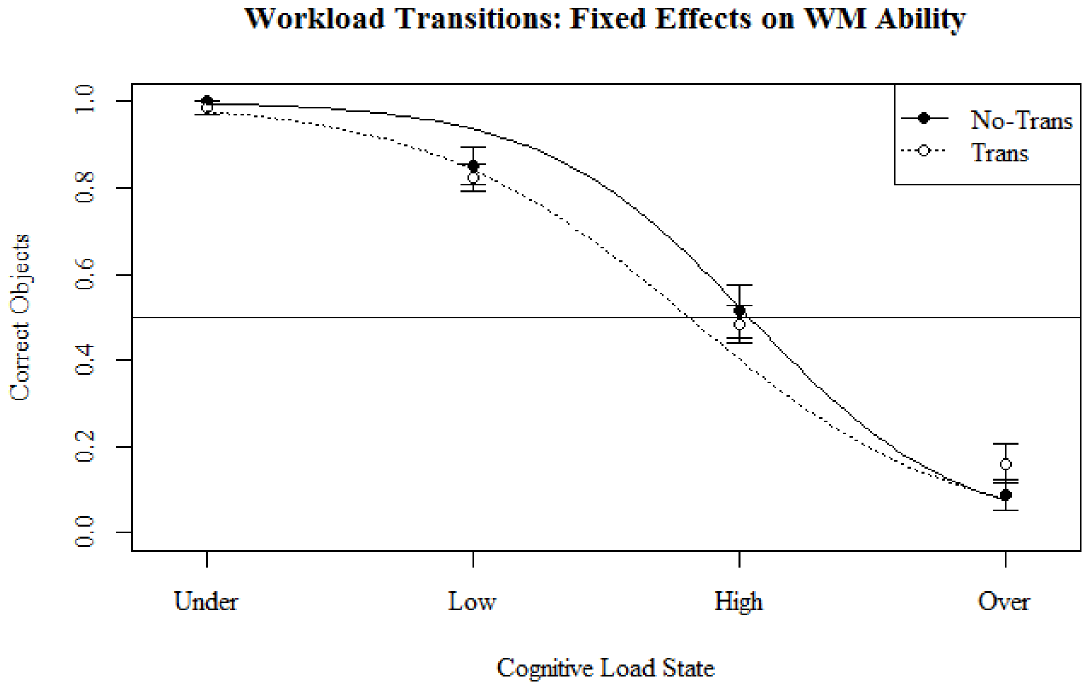

Figure 19. Correct trials as a function of cognitive load state and transition condition.

PSE, and linear slopes for the workload transitions condition all failed to reject the null hypothesis when compared to the effects of the no transition condition. Equivalence comparisons were performed to determine if there was evidence to accept the null hypothesis of no difference between the conditions. The estimates and 95% confidence intervals for transition PSE (figure 20) and linear slope (figure 21) effects failed the test of equivalence. One tail of the transition PSE confidence interval was not bounded by the no-transition PSE confidence interval, and both the estimate and one of the tails of the transition linear slope confidence interval were not bound by the no-transition confidence interval. This suggests that both tests were inconclusive and there is neither evidence to accept nor reject the null hypotheses regarding workload transition effects on PSE and logistic slope.

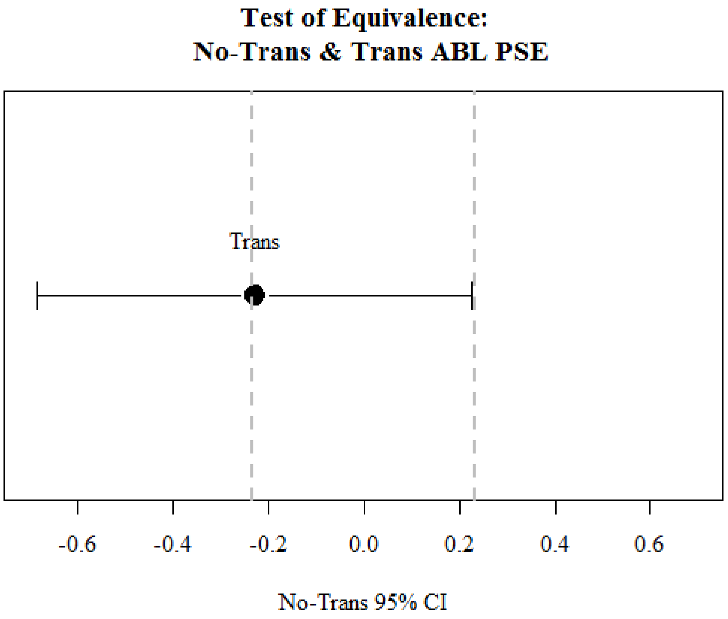

Figure 20. Correct trials beta coefficient and 95% confidence interval of difference between the PSE of workload transitions and no-transitions relative to the 95% confidence interval of the no-transition PSE estimate.

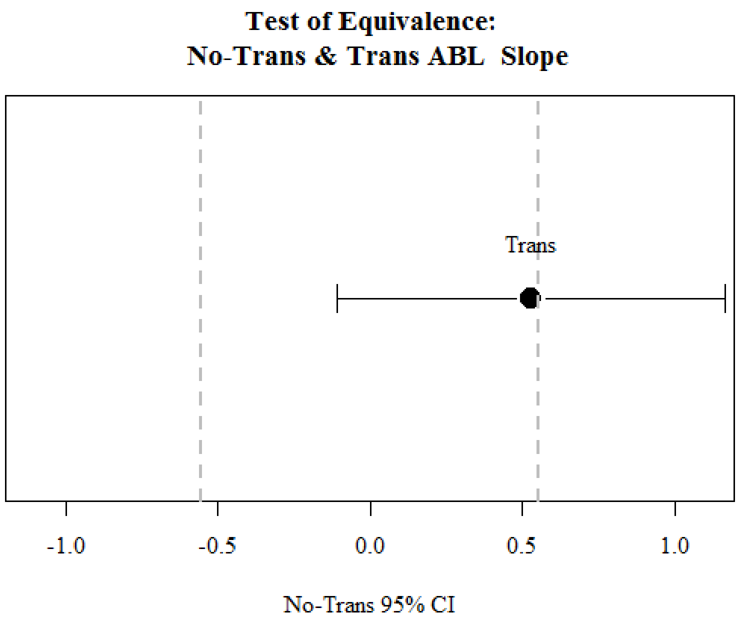

Figure 21. Correct trials beta coefficient and 95% confidence interval of difference between the linear slope of workload transitions and no-transitions relative to the 95% confidence interval of the no-transitions linear slope estimate.

NASA TLX: Mental Demand

The most parsimonious linear mixed effects model among those tested with BIC specified a linear slope of workload state interacting with increasing and decreasing workload transitions, and the random effects of participant intercept and linear slope. The fixed effects estimates are reported in table 11. The fixed effect slopes of correct trials are plotted across cognitive load states in figure 22.

Table 16.

Perceived Mental Demand as a Function of Cognitive Load State

	Mental Demand	
	B	*CI*
Fixed		
No-Trans Mean	39.19 ***	33.03 to 43.36
No-Trans Slope	19.33 ***	15.42 to 23.23
Inc-Trans Mean	-3.55	-7.32 to 2.14E-01
Dec-Trans Mean	11.27 ***	7.51 to 15.04
Inc-Trans Slope	0.38	-3.36 to 4.13
Dec-Trans Slope	-2.71	-6.45 to 1.04
	Var	*Std. Dev*
Random		
Intercept	1.46E+02	1.21E+01
Cognitive Load State	4.98E+01	7.05E+00
N	17	
Observations	170	

Notes * p<.05 ** p<.01 *** p<.001

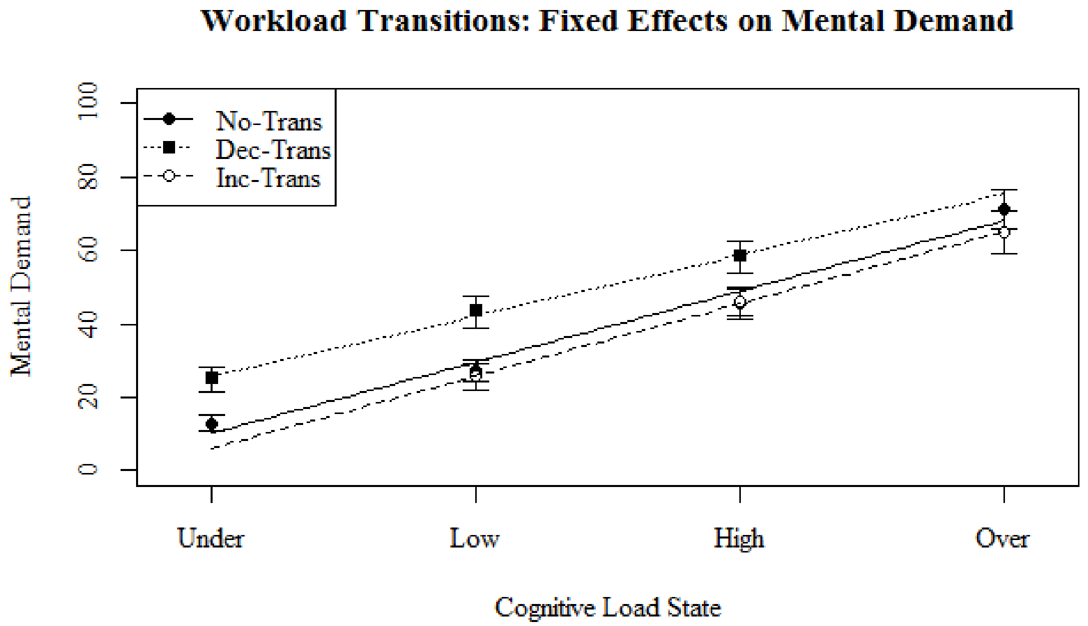

Figure 22. NASA TLX: Mental Demand as a function of cognitive load state and transition condition.

As in previous observations increasing cognitive load increased the perceived mental demand of the task. As would have been expected the mean reported mental demand was higher for decreasing workload transitions. This was because during the decreasing condition participants spent more total time at a higher cognitive load than the no-transitions condition, suggesting an accurate aggregation of the difficulty of the task demands. However, it would then be expected that increasing workload transitions would have a lower mean mental demand since more time was spent at a lower cognitive load. This difference was not observed.

Mental demand mean, and linear slope for increasing workload transition failed to reject the null hypothesis in comparison to the equivalent effects of the no transition condition. Equivalence comparisons were performed to determine if there is evidence to accept the null hypothesis of no difference between the conditions. The 95% confidence intervals for the mean of increasing transitions (figure 23) and linear slope (figure 21) effects failed the test of equivalence. For both effects one tail of their confidence intervals was not bound by the 95% confidence intervals of their counterpart effects. This suggests that both tests were inconclusive and there is neither evidence to accept nor reject the null hypotheses regarding increaseing workload transition effects on mean mental demand and linear slope as a function of cognitive load state.

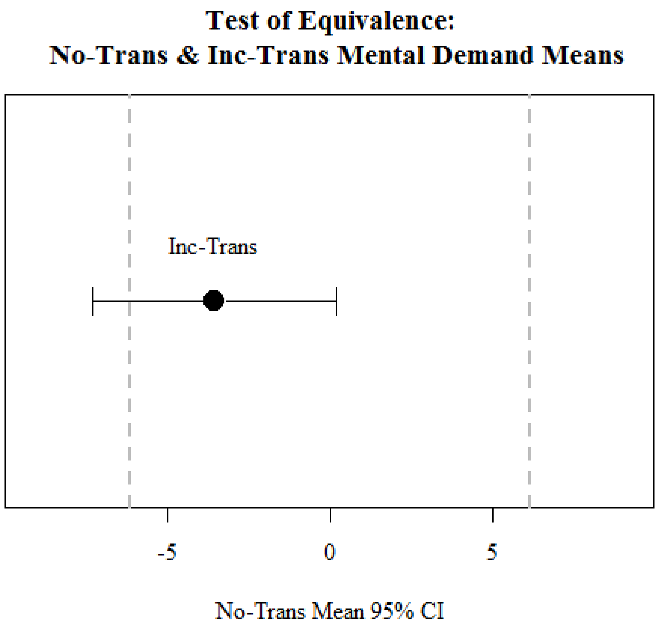

Figure 23. NASA TLX: Mental Demand beta coefficient and 95% confidence interval of difference between the mean of increasing workload transitions and no-transitions relative to the 95% confidence interval of the no-transition mean estimate.

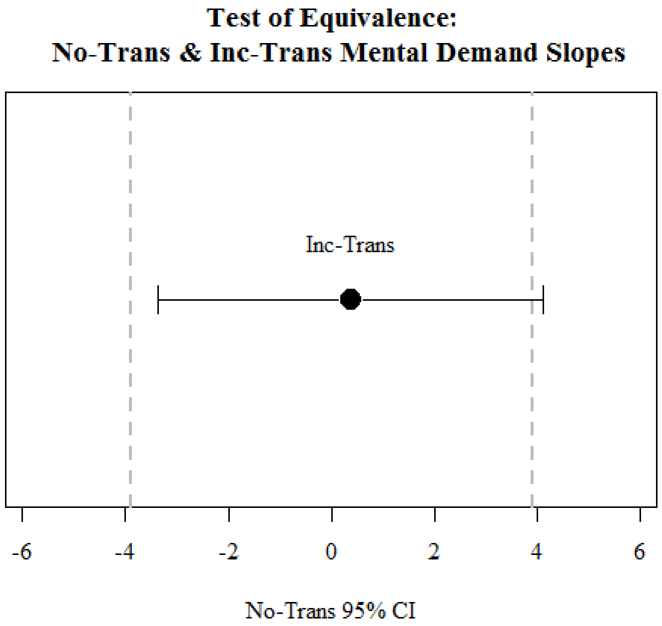

Figure 24. NASA TLX: Mental Demand beta coefficient and 95% confidence interval of difference between the slope of increasing workload transitions and no-transitions relative to the 95% confidence interval of the no-transition slope estimate.

Prefrontal Hemodynamics

Since only the cubic effects in LLOFC were replicated in study two, and these effects were primarily used in selecting individual's cognitive load states only the hemodynamics of LLOFC were analyzed for effects of workload transitions. The most parsimonious linear mixed effects model among those tested with BIC specified a polynomial cubic slope of cognitive load state interacting with workload transitions, and the random effects of participant intercept and trial slope. The fixed effects estimates are reported in table 12. The fixed effect slopes of LLOFC HbO (figure 25) and HbR (figure 26) are plotted across cognitive load states as a function of workload transition condition.

Table 17.

Effects of Cognitive Load State on Relative Concentrations of HbO and HbR in Frontal Cortex

	Left Lateral Orbitofrontal Cortex			
	HbO		HbR	
	B	*CI*	*B*	*CI*
Fixed				
No-Trans Intercept	-2.71E+00 *	-5.35E+00 to -6.82E-02	1.34E+00	-2.57E-01 to 2.93E+00
Trans Intercept	3.01E+00	-8.95E-01 to 6.92E+00	-2.29E-02	-2.39E+00 to 2.35E+00
No-Trans WM Load	4.87E+00 *	7.10E-01 to 9.03E+00	-2.26E+00	-4.79E+00 to 2.74E-01
No-Trans WM Load^2	-2.34E+00 *	-4.19E+00 to -4.84E-01	8.48E-01	-2.81E-01 to 1.98E+00
No-Trans WM Load^3	3.23E-01*	7.68E-02 to 5.70E-01	-9.33E-02	-2.43E-01 to 5.67E-02
Trans WM Load	-6.26E+00 *	-12.19E+00 to -3.02E-01	-5.46E-01	-4.15E+00 to 3.06E+00
Trans WM Load^2	3.14 E+00*	5.10E-01 to 5.77E+00	5.30E-01	-1.06E+00 to 2.12E+00
Trans WM Load^3	-4.46E-01 *	-7.96E-01 to -9.57E-02	-1.03E-01	-3.15E-01 to 1.09E-01
	Var	*Std. Dev*	*Var*	*Std. Dev*
Random				
Intercept	2.06E+00	1.44E+00	4.88E-01	6.98E-01
Trial	1.86E-03	4.31E-02	2.61E-04	1.61E-02
Residual	9.81E-01	9.90E-01	3.81E-01	6.17E-01
N	17		17	
Observations	646		646	
Notes * p<.05 ** p<.01 *** p<.001				

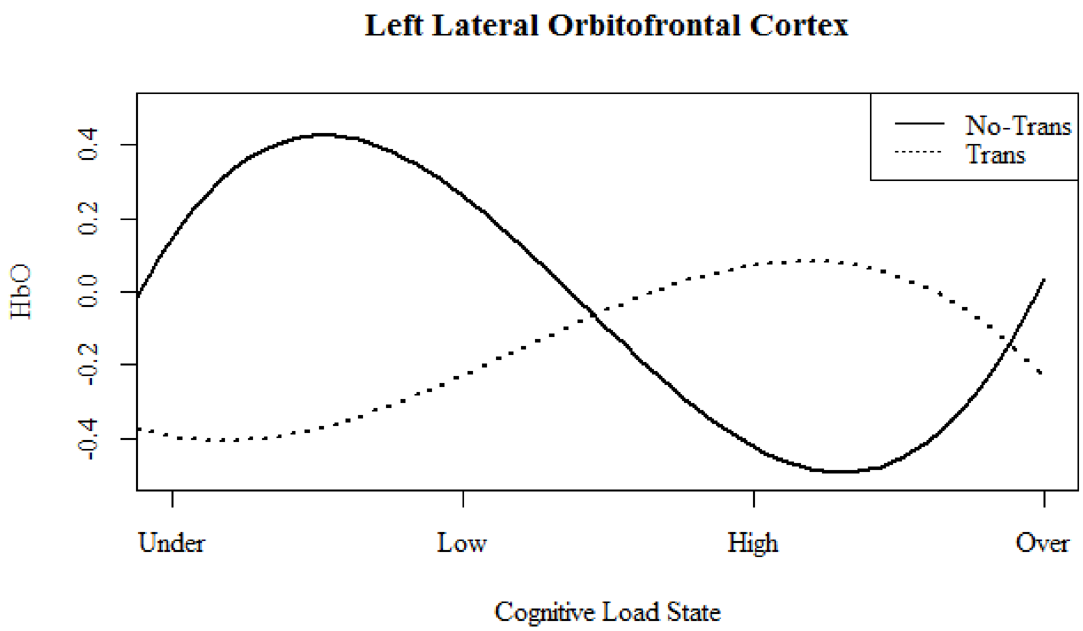

Figure 25. LLOFC relative oxygenated hemoglobin as a function of cognitive load state and workload transition condition.

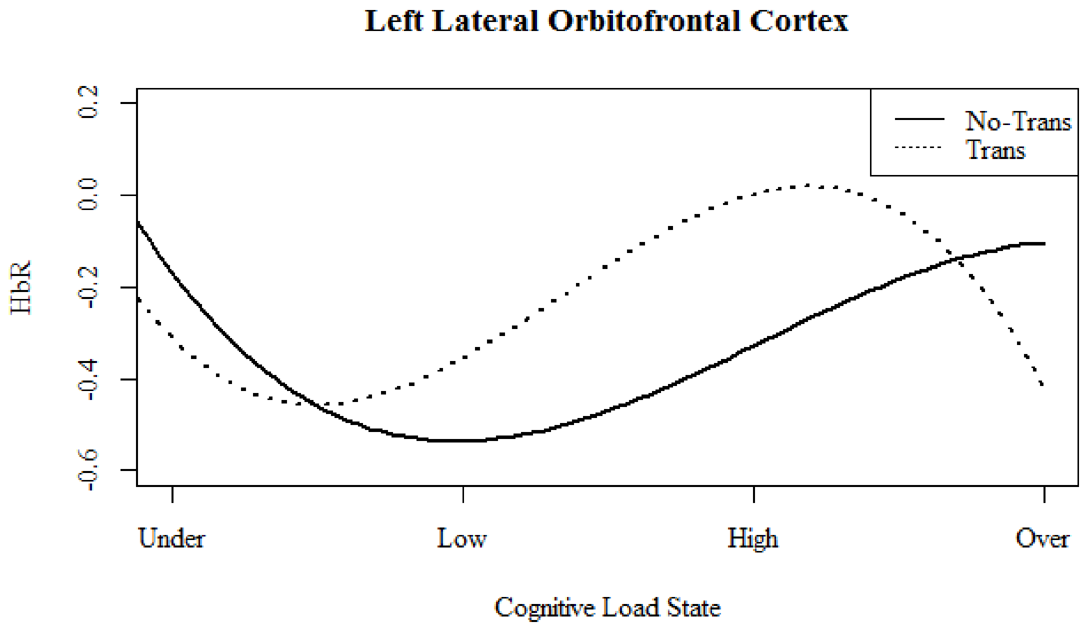

Figure 26. LLOFC relative deoxygenated hemoglobin as a function of cognitive load state and workload transition condition.

The cubic function of HbO for no-transitions was significant and cohered with the direction of slopes observed for the chromophore in LLOFC for study one and session one of study two. Importantly, no cognitive load states' HbO concentration manifested at a stationary point, instead as per our design each cognitive load state HbO manifested either to the left or right of each stationary point. The inflection point in the no transition condition could also be used as in the observations of study one and study two session one to distinguish between low and high cognitive load states. The presence of workload transitions significantly altered the shape of the cubic function of HbO in LLOFC. Workload transitions effectively flipped the signs of each of the functions slopes. It appears as though the presence of workload transitions caused a phase shift in the HbO function. Similar to the observations in LLOFC for study one, cognitive load states without transitions did not produce a significant cubic effect, and it is unclear if the presence of workload transitions significantly altered the shape of the HbR function.

DISCUSSION: SESSION TWO

Session two evaluated if workload transitions altered the previously observed relationships between performance, subjective report and prefrontal hemodynamics, and cognitive load. Workload transition have been shown to have detrimental effects on behavior and perceived mental demands. However, previous studies had not classified different cognitive load states independent of behavioral performance or subjective report. Here cognitive load states were classified on an individual basis based on prefrontal hemodynamics and workload transitions either increased, or decreased to these identified states. Comparisons of the effects of workload transitions were made to identical time points at identical load levels where no workload transition had occurred.

Behavioral measures of correctly reported objects and correctly performed trials were not strongly affected by workload transitions. We observed evidence that the number of spatial objects that could be reported across cognitive load states was effectively independent of the presence of workload transitions. This runs against the majority of behavioral findings regarding workload transitions. Workload transitions consistently have detrimental effects on performance and in some cases positive effects. However, it is unclear that workload transitions had absolutely no effect on task performance. While inconclusive, there is a trend that workload transitions diminished individual’s ability to perform a trial flawlessly. The divergence between these behavioral measures is interesting considering the two should be strongly related. It is difficult to draw strong conclusions from the behavioral data due to the failure of the correct trials test. However, the divergence between the two measures raises the question as to whether behavioral measures alone are enough to observe the full impact of workload transitions on cognition.

Unlike behavioral measures of this task, subjective measures were sensitive to the presence and direction of workload transitions. Specifically, decreasing transitions increased the aggregate perceived mental demand of a trial block, and increasing transitions trended toward indifference from no-transitions. This simplest explanation for these results is that individuals were highly influenced by the highest cognitive load experienced during a block. In essence workload transitions had no meaningful effects on subjective report, the perceived cognitive load of a block was just the highest cognitive load experienced. So while subjective measures were statistically sensitive to the workload transition manipulations, the effects observed reveal little about the underlying cognition involved in workload transitions.

While the behavioral and subjective measures held little insight, the prefrontal hemodynamics observed across cognitive load states were substantially changed by the presence of workload transitions. Across two groups of individuals and within two time points in the second group; HbO in the optical channel over LLOFC had a distinct cubic relationship with increasing spatial memory load. From 1 to 3 objects HbO increased, beginning to fall between 4 to 7 objects, and once again rising from 8 to 10 objects. In session two of study two we observed that while going from the ‘underload’ cognitive load state to the ‘low’ cognitive load state HbO increased, but decreased while going from the ‘low’ cognitive load state to the ‘high’ cognitive load state, and finally increasing when going from the ‘high’ cognitive load state to the ‘overload’ cognitive load state. This relationship changed with the presentation of a workload transition, and this change was consistent regardless of whether the transitions was to a higher or lower cognitive load state. In essence, workload transitions caused the signs of the linear, quadratic, and cubic slopes to flip, those that were positive became negative, and those that were negative became positive. This change in a function that had been fairly consistent across three other measurements suggests a meaningful change in the cognition underlying the spatial working memory task.

Workload transitions do not simply increase cognitive load. If workload transitions only caused an increase in tasks cognitive load we would have observed considerably different functions for behavioral performance, subjective report, and prefrontal hemodynamics. First, the quadratic slope for correctly reported objects should have been significantly more negative that what was observed leading to significantly poorer performance at higher load levels. Second, the slope of correct trials should have been more negative than what was observed, leading to less inconsistencies between the two behavioral measures and again poorer performance at the highest load levels. Third, we would have anticipated a significantly higher mean for mental demand on increasing workload transitions, similar to the mean observed during decreasing workload transitions. Hemodynamically, we would have anticipated HbO during the underload state following a workload transition to be higher, similar to that of low load when no transition had occurred. Similarly, we would have anticipated HbO during the overload state to be higher than what was observed. Alone none of these observations would be damning to workload transitions *as* simple increases in mental workload. However, given that each measure suggests against such an interpretation leads us to believe that workload transitions have more complicated effects on cognition than simply increasing cognitive load.

The change in prefrontal hemodynamics provides evidence that workload transitions affect cognition, however the nature of that affect is unclear. While we have provided evidence against increases in cognitive load as a sufficient explanation for the affect, we cannot rule out its role entirely. The cubic function we found in LLOFC also suggests that there is another brain region that acts as a moderator to LLOFC within a greater cognitive load network. The activity of this region is hypothesized (given the observed function in LLOFC) to coincide with the onset of compensatory cognitive strategies as cognitive load exceeds working memory capacity. Examining the interaction between this yet unobserved brain region, LLOFC and workload transitions could shed further light on the nature of the cognitive changes underlying the hemodynamic changes induced by workload transitions.

CONCLUSION

Excellent human performance and skill acquisition require matching the demands of tasks and training to an individual's cognitive capacity (Chandler & Sweller, 1991; Parasuraman, Sheridan & Wickens, 2008). In order to adapt tasks and training to individuals we must be able to classify cognitive load and cognitive states on an individual basis. In the aforementioned studies, we examined cognitive load levels and states across subjective, behavioral and hemodynamic measures. In two different random samples and at two different time points in the second sample we observed consistent effects of spatial memory load on cognitive load across all measures. When, the replicability of psychological effects is currently under question (Open Science Collaboration, 2015), the consistency of our observations cannot be understated.

Although our observations were consistent across samples, their utility was not equivalent. The NASA TLX measure of cognitive load had a linear relationship with spatial memory load. The linearity of this measure meant at best we could differentiate one cognitive load level from another. Similarly, behavioral measures could differentiate cognitive load levels; but to a lesser degreed due to the nonlinear nature of their effects. The nonlinear properties of the behavioral effects meant they were useful in indexing cognitive ability and minimally a cognitive overload state. It was the nonlinearities present in prefrontal hemodynamics that afforded them similar diagnosticity. Prefrontal hemodynamics were also able to index ability and were able to provide objective measures of cognitive load states via function differentiation.

The properties observed between cognitive load states indexed via hemodynamics can inform system design. The state observed between one and three objects coheres with previous estimates of working memory capacity which is usually estimated at four chunks of information (Conway, 2010). In system design where working memory is highlighted as an a priori design consideration, four chunks of information is believed to be the maximal amount of information that can be presented to a user (Wickens et al., 2013). However, we show that the nature of the task needs to be accounted for. In tasks that reward minimal errors, keeping information processing under an individual's working memory capacity (i.e. one to five objects) will result in maximal performance. However, if a task rewards maximizing hits our results suggest that keeping processing under the capacity limit will not maximize performance. Instead, in these tasks maximal performance in achieved through providing the maximal information without inducing an overload state (i.e. five to eight objects).

The effects observed in the optical channel over LLOFC with increasing cognitive load also alters previous findings regarding the attenuation of prefrontal activity in the presence of cognitive overload. The attenuation hypothesis stated that increasing demand to the point of cognitive overload attenuated the response to cognitive load in prefrontal cortex (Durantin et al., 2013). In some sense our observations still cohere with this hypothesis. Indeed attenuation does occur in prefrontal hemodynamics as errors begin to arise, however these are only errors in regards to flawless performance. They do not represent overload in the traditional sense. Overload results in a total breakdown in task performance (Grier et al., 2008). This did not occur in our data till about eight objects, where performance across all measures is in decline. This also coincided with a facilitation of hemodynamic activity.

In light of expanding on the attenuation hypothesis, we should also try and understand why we did not observe a state of underload, and if there are yet to be observed cognitive states beyond the state we classify as cognitive overload. The state of underload is notorious for being difficult to measure and in future work cognitive state classification and workload transition tests may need to be adapted to a task that has the correct properties to induce this important cognitive state. At the same time previous work assumed an attenuation hypothesis for cognitive overload only because the range of task demands was to narrow, this begs the question as to whether there are other cognitive states related to increased task demands that could not observed in the current paradigm. How would individuals respond to fifteen or twenty objects, would the hemodynamic response asymptote, would it oscillate into other cognitive states? It is possible that extending the range of observed task demands could alter the model observed here.

We also used our success in objectively classifying cognitive load states to test the effects of workload transitions. Workload transition effects have been consistently observed in subjective measures of workload but we observed no direct effects. Three of the previously observed effects were relevant within the context of the current study. Specifically, a resistance to change in perceived cognitive load (i.e. hysteresis) (Morgan & Hancock, 2010), an exaggerated propensity to change in perceived cognitive load (i.e. relativistic) (Hancock et al., 1995) and biasing cognitive load aggregation toward the load experienced during a workload transition (Thorton, 1985). None of our subjective effects could be classified as relativistic. However, decreasing transitions did produce subjective effects that are similar to those of hysteresis. In that the reported workload was similar to the workload prior to the transition. At the same time increasing workload transitions showed evidence of biasing of the subjective report to the cognitive load experienced during the workload transition. There are two ways of interpreting this evidence. Either, there are different subjective effects for increasing and decreasing workload transitions, or there is no particular effect of either and instead it was overall task demands that biased subjective report. More specifically, individuals during no-transitions, increasing transitions and decreasing transitions only reported their perceived cognitive load for the highest task demands experienced on a given block. Given the simplicity of the second explanation it is the more favorable option.

Similar to our observations regarding subjective measures of cognitive load, we did not observe the strong effects we expected in behavioral performance. There is a substantial body of research showing effects of workload transitions. The prominent effect be a decrease in performance, and this is independent of whether the transition is to a higher or lower cognitive load (Cox-Fuenzalida et al., 2006). Here, workload transitions had little to no effect on an individual’s ability to maintain and recall spatial working memory objects. However, there was a trend for workload transitions decreasing the probability of flawless recall. Yet, this is a more nuanced effect than what we expected to observe. It is unlikely that the failure to replicate behavioral decrements from workload transitions is due to the transitions test occurring in the second session. When we examine performance across sessions one and two, there is little change in performance. This lack of change overtime was expected, improvements in this task require either extensive training or non-invasive brain stimulation (McKendrick et al., 2014; McKendrick et al., 2015). There was also no evidence of fatigue, which has been observed in previous behavioral and hemodynamic measure of this task. We also feel that expectancy of the transition had little effect on the outcome. Previous work in this area has shown that the knowledge of whether a workload transition will or will not occur does not change the workload transitions effect of behavior (Goldberg & Stewart, 1980). We also do not believe that the workload transitions we employed were to subtle. Each transition was to a markedly different level of performance, and transitions subtler than those employed here have still successfully altered performance (Cox-Fuenzalida et al., 2007)

Our paradigm did deviate from traditional workload transition paradigms in two ways, and either one of these deviations could have altered the effect of workload transitions on performance. First, we altered cognitive load via altering memory load. The vast majority of previous workload transition studies have used stimulus event rate to alter cognitive load (Cumming & Croft, 1973; Krulewitz, Warm & Wohl, 1975;

Goldberg & Steward, 1980; Hancock et al., 1995; Cox-Fuenzalida et al., 2004; Cox-Fuenzalida et al., 2005; Cox-Fuenzalida et al., 2006; Cox-Fuenzalida, 2007; Bowers et al., 2014). Perhaps, changes in the amount of information to be processed has less of an effect on the mechanisms that underlie workload transitions than does the amount of time available to process that information. In some sense this coheres with our hemodynamic observations as it was clear that workload transition effects could not be sufficiently explained by an increase in cognitive load. The other change we made to traditional workload transition paradigms is we adapted workload transitions to the cognitive states of each individual. Another study that attempted to adapt transitions to individual performance was also unsuccessful in replicating robust workload transition effects (Bowers et al., 2014). This could be taken to suggest that some of the previous findings of workload transitions have more to do with individual difference in cognitive capacity than the presence of the actual transitions. Suggesting that the actual effect of workload transitions is smaller than previously thought. Future work should look to test this outright and determine, if adaptation actually diminishes the observed effects of workload transitions.

It is possible that workload transitions have a very specific effect on cognition. From our results it appears that workload transitions are disruptive to the integration of cognitive processes that make-up working memory. Due to this disruption, individuals default to a simpler model of the task with a greater emphasis on satisficing (i.e. just good enough performance). We find evidence of this in our measures of behavior. Specifically, the deviation between individual’s ability to correctly report objects and their ability to perform flawlessly. A disruption of process integration and greater emphasis on satisficing could explain why complete task execution is on the decline with no observable change in how many objects individuals are able to report. This trend toward cognitive satisficing could also explain why in our subjective measure of cognitive load individual's seemed to just report the highest workload experienced. There is also evidence for disruption of process integration when examining the effects of workload transitions on prefrontal hemodynamics. In the absence of transitions the onset of activation attenuation occurs at approximately three objects, and we argue here that this attenuation coincides with the onset of compensatory executive functions to enhance performance. In the presence of workload transitions attenuation occurs at much higher task demands. Specifically, task demands that are associated with a high state of cognitive load, which in this task is about five to eight objects. Attenuation could be occurring at a higher cognitive state because the mechanisms for integrating compensatory executive functions with primary task performance are operating less efficiently. It is possible that the other brain regions that moderate the function in the LLOFC optical channel and compensatory functions require a greater level of activation following workload transitions. We also find evidence for our disruption hypothesis if we compare the magnitude of our effects to those previously observed following workload transitions. Our studies employed a discrete working memory task and we observed minimal effects of workload transitions on behavior. In the previous literature where more robust effects were observed continuous tasks reliant on manipulating event rate were used. In line with our hypothesis one would expect to see greater effects of disrupted cognitive process integration in continuous tasks relative to discrete tasks. This is due to the effects of inefficient or failed cognitive process integration compounding in continuous tasks but being isolated to single trials in discrete tasks.

We can make two other explicit predictions regarding workload transitions if we assume that they cause a disruption in cognitive process integration. First in line with greater effects being observed in continuous tasks, tasks composed of a greater number of cognitive components or that have more complex responses should be more negatively affected by workload transitions. This runs counter to our initial assumption that research on workload transitions should focus primarily on basic tasks, and also explains why workload transitions are of such a concern in real work. Second, our observed effect in prefrontal hemodynamics and its relationship to our disruption hypothesis suggest that workload transitions should have specific network effects. Effectively, workload transitions should alter or retard the functional relationship between brain regions associated with the onset of attenuated activity in lateral prefrontal cortex as cognitive load increases. The observation of these two effects would provide direct evidence for our hypothesis that workload transition effects are caused by a disruption of cognitive process integration and should be a focus of future work on workload transitions and cognitive load state classification.

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BIOGRAPHY

Ryan McKendrick received his Bachelors with honors in Psychology and high honors in Philosophy from Rutgers University in 2010. He went on to receive his Master of Arts in Psychology from George Mason University in 2014. He then received his Doctorate in Psychology with a concentration in Human Factors and Applied Cognition from George Mason University in 2016.